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THESIS

EASTERN NORTH CAROLINA MARINE CORPS FORCES AND INSTALLATIONS HIGH INTENSITY HURRICANE EVACUATION DECISION SUPPORT

by

Brian Taylor

June 2007

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13. ABSTRACT (maximum 200 words)

Eastern North Carolina Marine Corps Forces and Installations (ENCMCFI) is located on the Atlantic coast of North Carolina and is therefore vulnerable to a major hurricane. Base commanders must weigh the substantial costs of evacuation – approximately $30-$50M for a full evacuation – against the risk posed by the effects of the storm if personnel are not evacuated. The purpose of this thesis is to provide a decision aid for base commanders to identify forecast conditions that indicate the need to initiate an evacuation. In order to assess the probability of a direct strike to ENCMCFI posed by a new storm, this thesis proposes using National Hurricane Center forecasts combined with a statistical model of historical forecast errors. Additionally an analysis of evacuation assets available and the distances to primary evacuation locations is also conducted to identify available options for evacuation at the decision time. A series of decision rules is created to determine whether, based on the current storm forecast and the available evacuation assets, evacuation is warranted now or whether it is better to wait until the next forecast is issued. The results of this study indicate that the risk of riding out the storm at ENCMCFI and the transportation risk of evacuating are approximately equal given the current evacuation plan and the required decision lead time.

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EASTERN NORTH CAROLINA MARINE CORPS FORCES AND INSTALLATIONS HIGH INTENSITY HURRICANE EVACUATION DECISION SUPPORT

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Submitted in partial fulfillment of the
requirements for the degree of

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Eastern North Carolina Marine Corps Forces and Installations (ENCMCFI) is located on the Atlantic coast of North Carolina and is therefore vulnerable to a major hurricane. Base commanders must weigh the substantial costs of evacuation – approximately $30-$50M for a full evacuation – against the risk posed by the effects of the storm if personnel are not evacuated. The purpose of this thesis is to provide a decision aid for base commanders to identify forecast conditions that indicate the need to initiate an evacuation. In order to assess the probability of a direct strike to ENCMCFI posed by a new storm, this thesis proposes using National Hurricane Center forecasts combined with a statistical model of historical forecast errors. Additionally an analysis of evacuation assets available and the distances to primary evacuation locations is also conducted to identify available options for evacuation at the decision time. A series of decision rules is created to determine whether, based on the current storm forecast and the available evacuation assets, evacuation is warranted now or whether it is better to wait until the next forecast is issued. The results of this study indicate that the risk of riding out the storm at ENCMCFI and the transportation risk of evacuating are approximately equal given the current evacuation plan and the required decision lead time.

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EXECUTIVE SUMMARY

Eastern North Carolina Marine Corps Forces and Installations (ENCMCFI) is located on the Atlantic coast of North Carolina and is vulnerable to damage from a major hurricane. Base commanders must weigh the substantial costs of evacuation – approximately \$30-\$50M for a full evacuation – against the risk posed by the effects of the storm if personnel are not evacuated. Evacuation planning is important to ENCMCFI due to the requirement for tenant forces to provide continuous war-fighting capabilities. A large student population in excess of 5,000 Marines without personal transportation complicates the problem. The variables considered for an evacuation decision are the weather analysis conducted by meteorology personnel, and the evacuation transportation analysis performed by the operations department. Both variables are to the evacuation decision. Two obstacles hinder decision making: operations personnel do not understand the nuances of hurricane forecasting and meteorology personnel do not understand the time and distance constraints for a large scale evacuation. The purpose of this thesis is to bridge the gap between meteorology and operations to assess the costs and risks involved in the evacuation decision. The thesis also assists the base commander in identifying forecast conditions that indicate the need to initiate an evacuation using storm forecast information and current transportation asset availability information.

The landfall of a major hurricane in North Carolina is a high-impact, low-frequency event: only one category 4+ hurricane (on the Saffir-Simpson Scale) has made landfall in North Carolina in the past 106 years. Hurricanes make landfall in North Carolina, on average, only once every 4 years. Structures identified as hurricane shelters at ENCMCFI are built to withstand wind speeds of 105 knots (kts). At 12-17 miles inland, ENCMCFI faces a minimal risk of storm surge. As a result, ENCMCFI only needs to evacuate in the event of a direct strike from a Category 3 or higher storm.

Base commanders must assess the risk posed by a given storm using hurricane forecasts from the National Hurricane Center (NHC). The NHC issues forecasts every six hours during a storm. The forecasts consist of position and intensity estimates at 12 or 24

hour increments for up to 120 hours into the future. However, the NHC does not provide estimates of the probability of 105 kts winds at ENCMCFI. In order to assess the probability of wind speeds greater than or equal to 105 kts at ENCMCFI, this thesis proposes using NHC forecasts combined with a statistical model of historical forecast errors. Distributions for the positional and maximum wind speed forecast errors for each forecast time period are created using historical forecast data for hurricanes from 1996-2005, together with estimates of the actual storm positions and intensities. These forecast errors are used along with the forecast values of storm positions and intensities to determine a distribution of winds speeds at ENCMCFI. The resulting model assumes that the wind speeds at ENCMCFI, at different times, are conditionally independent given the associated position and intensity storm forecasts.

A series of decision rules is created to determine whether, based on the current storm forecast, evacuation is warranted now or whether it is better to wait until the next forecast is issued. The evacuation decision must be made before arrival of tropical-storm force winds. Evacuation operations cannot occur in tropical-storm force winds. Factors in this decision are the direct costs of evacuation, the transportation risk costs, and the risk costs of storm effects. Evacuation costs include costs for vehicles as well as travel and lodging costs for all personnel evacuated. Transportation risk and storm risk costs are estimated using historical travel and hurricane data to determine expected per-capita injuries and fatalities. The storm risk costs are based on the distribution of wind speeds at ENCMCFI. The model of storm wind speeds at ENCMCFI is used to study the storm forecasts that would initiate an evacuation based on the storm risk costs rising to a level above that of the direct evacuation costs plus the transportation risk costs. The results of this study indicate that the expected risk of riding out the storm at ENCMCFI and the expected risk of evacuating are approximately equal given the current evacuation plan and the required decision lead time. This result is driven by uncertainty in the prediction of the location and the intensity of the storm 72 hours in the future.

I. INTRODUCTION

> **Evacuation:** removal of people from a dangerous or potentially dangerous place
>
> (McDuffie 2002).

A. ORIENTATION

Eastern North Carolina Marine Corps Forces and Installations (ENCMCFI) consists of three installations: Marine Corps Base Camp Lejeune, Marine Corps Air Station New River and Marine Corps Air Station Cherry Point. The bases are located on the southern coast of North Carolina where major hurricanes are high-impact, low-frequency events. Having a coastline along the Atlantic Ocean of 301 miles, a tidal coastline of 3,375 miles, and a geography that juts out into the North Atlantic, North Carolina has a long history of hurricanes (Figure 1). Only one category 4+ hurricane on the Saffir-Simpson Hurricane Scale (Table 1) has made landfall in North Carolina in the past 106 years − Hurricane Hazel in 1954. Overall, hurricanes make landfall in North Carolina on average only once every four years (State Climate Office of North Carolina, 2006).

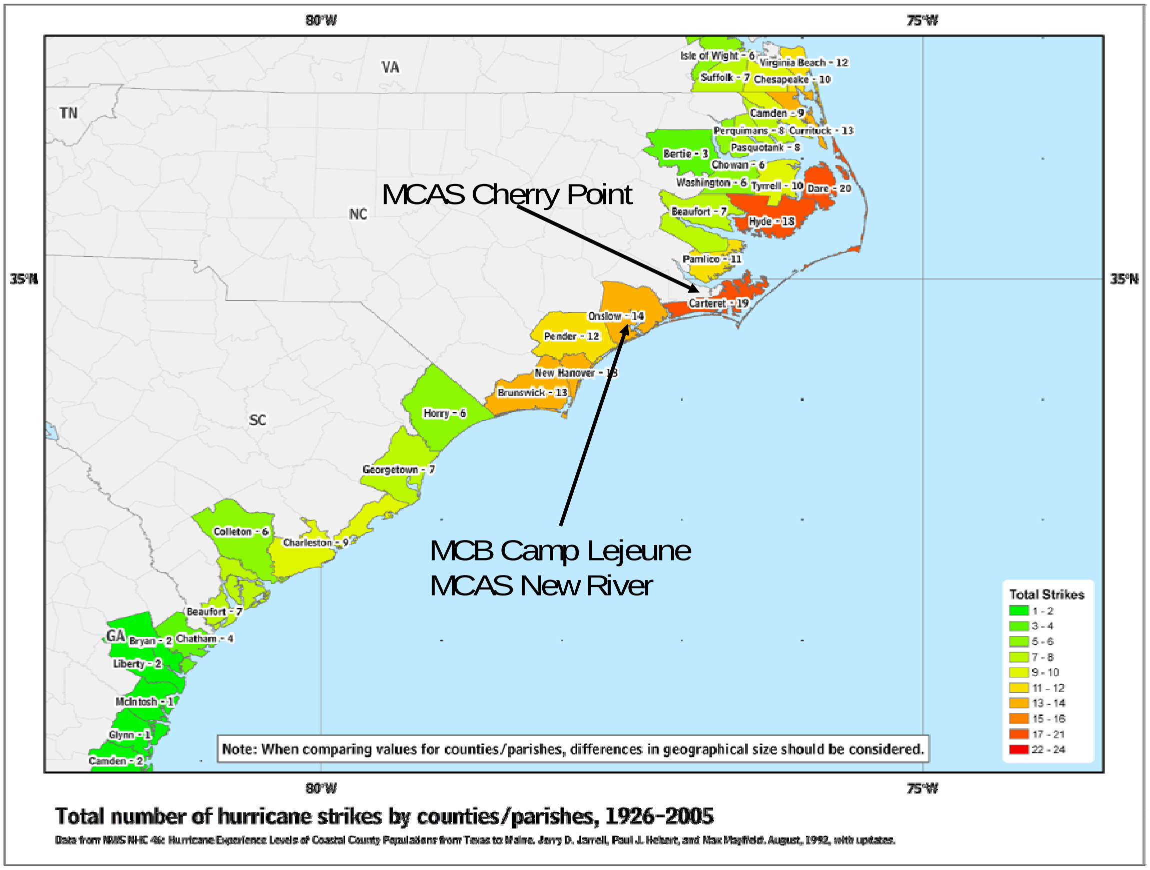

Figure 1. Map of Eastern North Carolina with number of hurricane strikes by county from 1926-2005 with location of bases in ENCMCFI indicated. Adapted from National Hurricane Center, Tropical Cyclone Climatology, 2007

While hurricanes occur frequently in North Carolina the number of high-intensity hurricanes to make landfall in North Carolina has been relatively small. Reliable classification of the intensity of tropical cyclones began in 1886. Since that time, there have been 951 tropical cyclones that have been recorded in the Atlantic Ocean and the Gulf of Mexico. Approximately 166 or 17.5% of those tropical cyclones passed within 300 miles of North Carolina (State Climate Office of North Carolina, 2007).

B. ENCMCFI HURRICANE BACKGROUND

When Hurricane Floyd threatened the North Carolina coast in September 1999, base commanders at ENCMCFI were faced with a Category 4 hurricane with winds of 115 knots (kts) approximately 72 hours from landfall with no evacuation plan in place. The decision was made for all ENCMCFI personnel to ride out the storm since there was no time to develop and execute an evacuation plan (T. Phillips, Director for Plans and Operations, ENEMCFI 2006). Fortunately, Hurricane Floyd diminished in intensity as it approached the coast, and eventually made landfall in North Carolina, approximately 60 miles south of ENCMCFI. Since that time, an evacuation plan has been developed to address the mechanics of how an evacuation should take place, but there is no clear set of circumstances that should initiate an evacuation. Evacuation for ENCMCFI is a special problem due to the need of the forces there to provide continuous war-fighting capabilities and a large student population, in excess of 5,000 Marines, without personal transportation. In addition there are several other populations of Marines and dependents that require government-supplied transportation (buses and vans) in the event of an evacuation, either because they are needed to maintain a continuous warfighting capability, or because they do not have personal transportation.

The variables considered for an evacuation decision are the weather analysis conducted by the meteorology personnel, and the evacuation transportation analysis performed by the operations department. Both are both critical pieces of information for the evacuation decision. Two elements hinder evacuation decision making; the operations personnel do not understand the nuances of hurricane forecasting and meteorology personnel do not understand time and distance constraints for a large-scale evacuation. The purpose of this thesis is to bridge the gap between meteorology and operations to assess the costs and risks involved in the evacuation decision. The thesis also provides guidance to the base commander in identifying forecast conditions that indicate the need to initiate an evacuation based on storm forecasts and current transportation asset availability.

C. TROPICAL CYCLONES

Hurricanes are a type of storm referred to as a tropical cyclone. The National Hurricane Center (NHC) defines a tropical cyclone as:

> A warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center. Once formed, a tropical cyclone is maintained by the extraction of heat energy from the ocean at high temperature and heat export at the low temperatures of the upper troposphere. In this they differ from extra-tropical cyclones, which derive their energy from horizontal temperature contrasts in the atmosphere (baroclinic effects) (National Weather Service, 2007e).

In the Atlantic Ocean, tropical cyclones typically begin as low-pressure disturbances in the atmosphere off the western coast of Africa. If conditions are right, this low pressure system is fueled by the latent heat of the southern Atlantic Ocean and becomes better organized. The system may begin to exhibit characteristics in the definition above which will cause the NHC to classify the storm as a tropical cyclone. When a tropical cyclone reaches a point where its sustained winds are in excess of 65 kts, the storm is classified as a hurricane. Hurricanes are assigned categories according to the Saffir-Simpson Hurricane scale based on their maximum sustained (1-minute average) wind speed at an elevation of 10 m. According to the NHC:

> The Saffir-Simpson Hurricane Scale is a 1-5 rating based on the hurricane's present intensity. This is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf and the shape of the coastline, in the landfall region. Note that all winds are using the U.S. 1-minute average. (National Weather Service, 2006a) (Table 1).

Saffir-Simpson Hurricane Scale				
Category	Barometric Pressure	Wind Speed	Storm Surge	Damage Potential
1 weak	28.94" or more 980.2mb or more	65 - 82kts 75 - 95mph	4 - 5ft 1.2 - 1.5m	Minimal damage to vegetation
2 moderate	28.50" - 28.93" 965.12 - 979.68mb	83 - 95kts 96 - 110mph	6 - 8ft 1.8 - 2.4m	Moderate damage to houses
3 strong	27.91"-28.49" 945.14 - 964.78mb	96 - 113kts 111 - 130mph	9 - 12ft 2.7 - 3.7m	Extensive damage to small buildings
4 very strong	27.17"-27.90" 920.08 - 944.80mb	114 - 135kts 131 - 155mph	13 - 18ft 3.9 - 5.5m	Extreme structural damage
5 devastating	< 27.17" < 920.08mb	> 135kts > 155mph	> 18ft > 5.5m	Catastrophic building failures possible

Table 1. Saffir-Simpson Hurricane Scale from State Climate Office of North Carolina

Tropical cyclones are enormous storms, often 300-500 miles across. The most obvious feature of a tropical cyclone is the eye which is an area of relative calm in the middle of the storm.

1. Wind Damage

A tropical cyclone's intensity is classified by the speed of its maximum winds. These maximum winds are located in a very small portion of the storm just on the outside of the eye of the storm in a portion of the cyclone referred to as the eye-wall (Figure 2), which is the barrier between the calm of the eye and the most ferocious winds of the storm. Wind intensity decreases as distance from the eye increases, but hurricane force winds, classified as winds in excess of 65 kts, can often extend hundreds of miles out from the eye. These winds flow in a counter-clockwise direction around the eye in the northern hemisphere and are parallel to the eye wall of the storm. Due to this rotation of the winds about the eye, the winds on the right side of the eye (relative to the storm's direction of forward motion, as seen from above), are parallel to the track of the storm. As a tropical cyclone moves over land, a point on the right side of the eye will feel the effects of the maximum winds of the storm amplified by the magnitude of the forward

speed of the storm. For this reason, the right side of the eye of a tropical cyclone experiences the strongest winds of the storm (National Weather Service, 2005b).

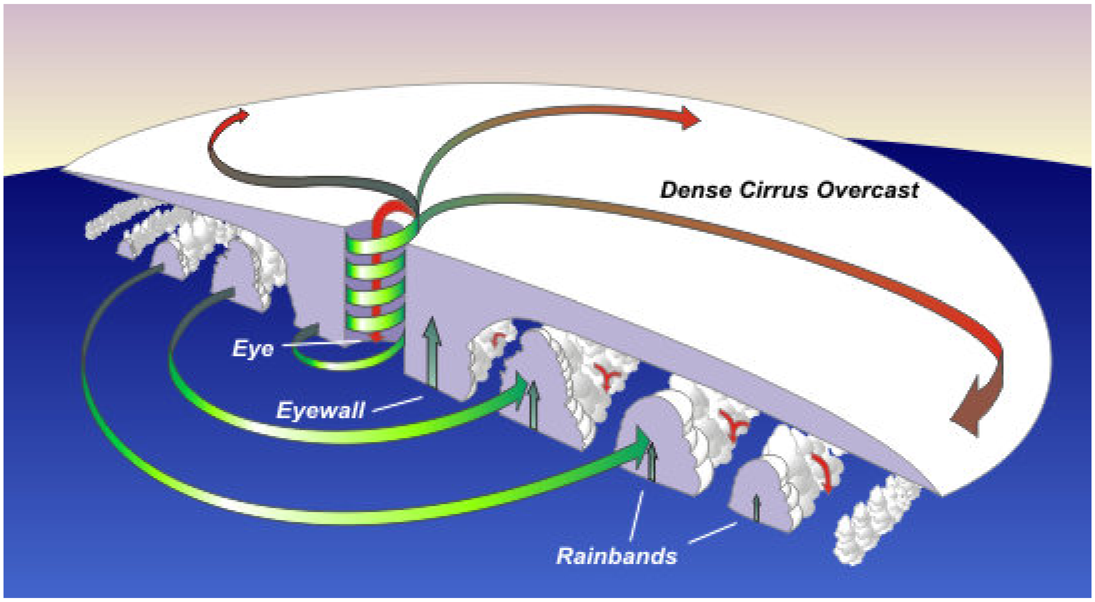

Figure 2. Diagram of the Anatomy of a Hurricane from the National Weather Service, Tropical Cyclone Structure, 2005

2. Storm Surge

While tropical cyclone forecast intensity reflects anticipated wind speeds, the effects of storm surge must also be considered: 9 out of 10 tropical cyclone fatalities are a result of flooding (not flying debris) (American Society of Civil Engineers, 2003). The NHC defines storm surge as:

> An abnormal rise in sea level accompanying a hurricane or other intense storm, and whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone. Storm surge is usually estimated by subtracting the normal or astronomic high tide from the observed storm tide (National Weather Service, 2007e).

Storm surge from tropical cyclones is a function of several factors in conjunction with the tropical cyclone. Time of day, local tides, wind pushing the water ashore, the

low pressure (vacuum) of the storm and underwater geography all have a profound impact on the level of storm surge expected as the tropical cyclone comes ashore. Figure 3 illustrates these factors.

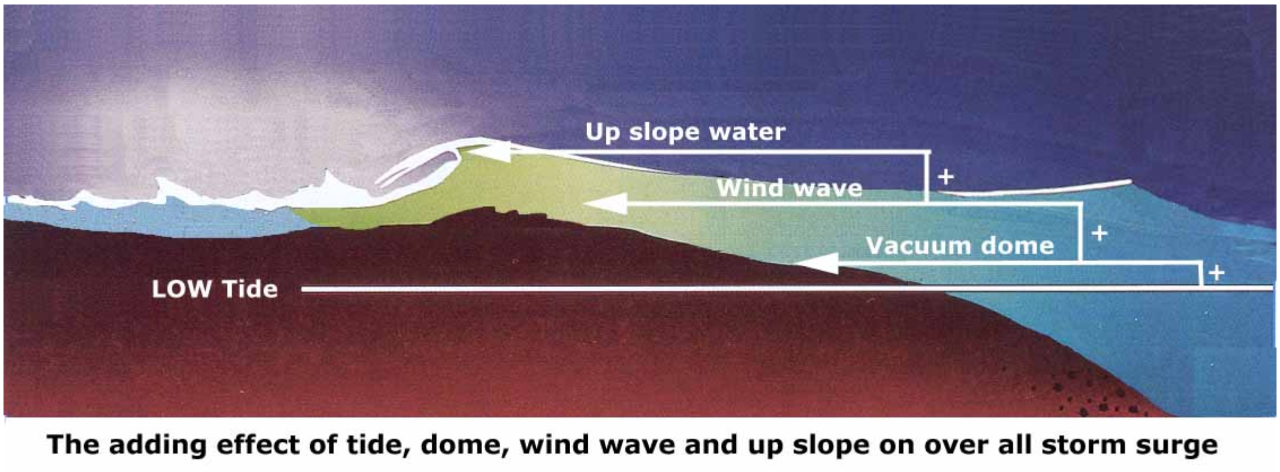

Figure 3. Depiction of causes of storm surge flooding from J. Wilkinson: Anatomy of a Hurricane

The level of storm surge depends on landfall location. It is possible to model storm surge levels using simulated storms. The anticipated storm surge level of can be assessed by using a model developed by the National Weather Service named: Sea, Lake and Overland Surges from Hurricanes (SLOSH). This model calculates potential surge heights from hurricanes as a function of approach direction, forward speed, and intensity. The results are independent of the point of landfall (USACE, 2002). The output from the SLOSH model is a map that indicates where flooding can be expected during different categories of tropical cyclone. Regions of two of the bases that comprise ENCMCFI, Camp Lejeune and MCAS New River, that can expect storm surge flooding from a category four or five hurricane are indicated in red in Figure 4. While extensive flooding is predicted at the coast, little flooding predicted at ENCMCFI even in category-5 storms. This is important since the main population centers of the base are located inland. The SLOSH model is continually being validated and improved:

> After a SLOSH model has been constructed for a coastal basin, verification is conducted as real-time operational runs in which available meteorological data from historical storms are input into the model. The computed surge heights are compared with those measured from historical

storms and, if necessary, adjustments are made to the input or basin data. In instances where the model has given realistic results in one area of a basin, but not in another, closer examination has often revealed inaccuracies in the representation of barrier heights or missing values in bathymetric or topographic data. The hurricanes used to verify the Pamlico Sound SLOSH Model are Donna (1960), Fran (1996), Floyd (1999) (USACE, 2002).

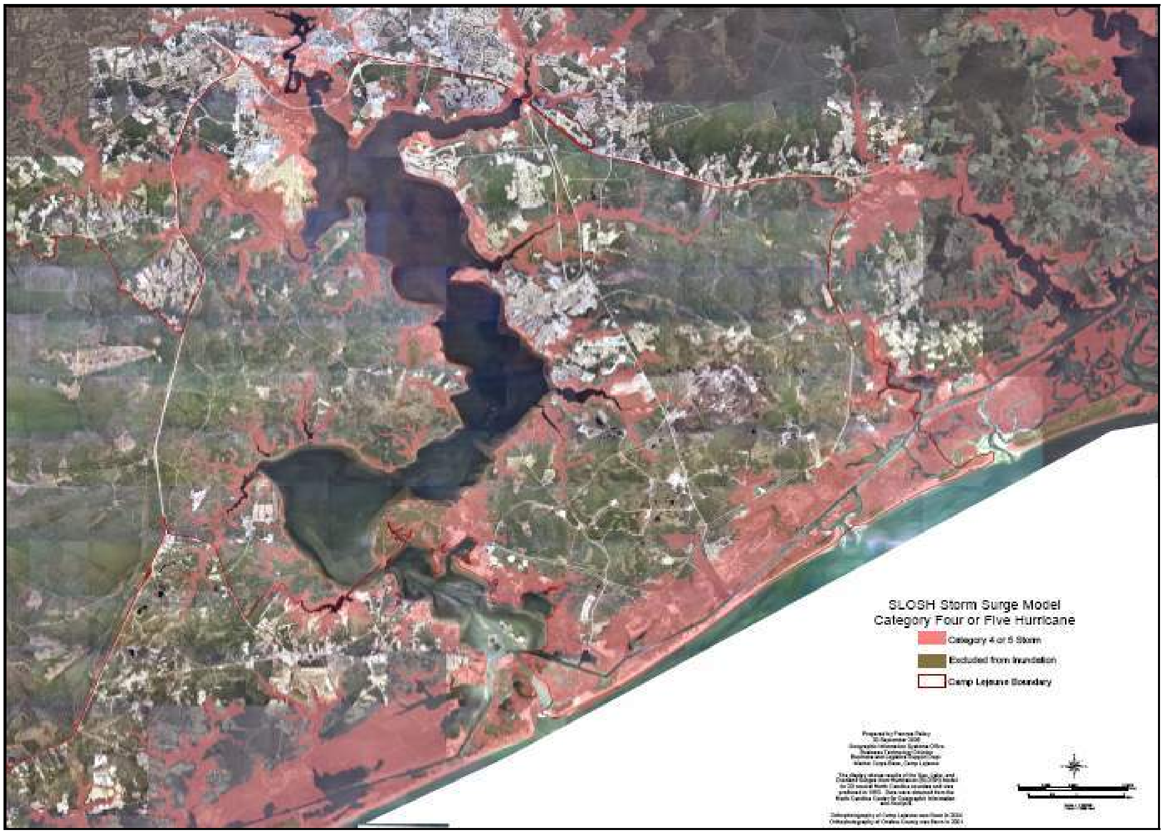

Figure 4. SLOSH map of Camp Lejeune, N.C. of Camp Lejeune

D. TROPICAL CYCLONE FORECASTS

When a low-pressure system or tropical wave develops in the Atlantic Ocean and demonstrates characteristics typical of a tropical cyclone, NHC forecasters begin tracking and forecasting that storm. The forecasts are a result of several models, including numerical global weather models that use global weather patterns to create forecast tracks. Forecasters at NHC use these data as well as satellite imagery and data collected from aircraft flying through the storm to create an official forecast of the tropical cyclone.

Official forecasts are issued by NHC every 6 hours for time periods 12, 24, 36, 48, 72, 96 and 120 hours into the future. The forecasts include the projected position of the eye and the estimated intensity of the storm. These forecasts are issued in both a numerical format and with the graphical depiction shown in Figure 5.

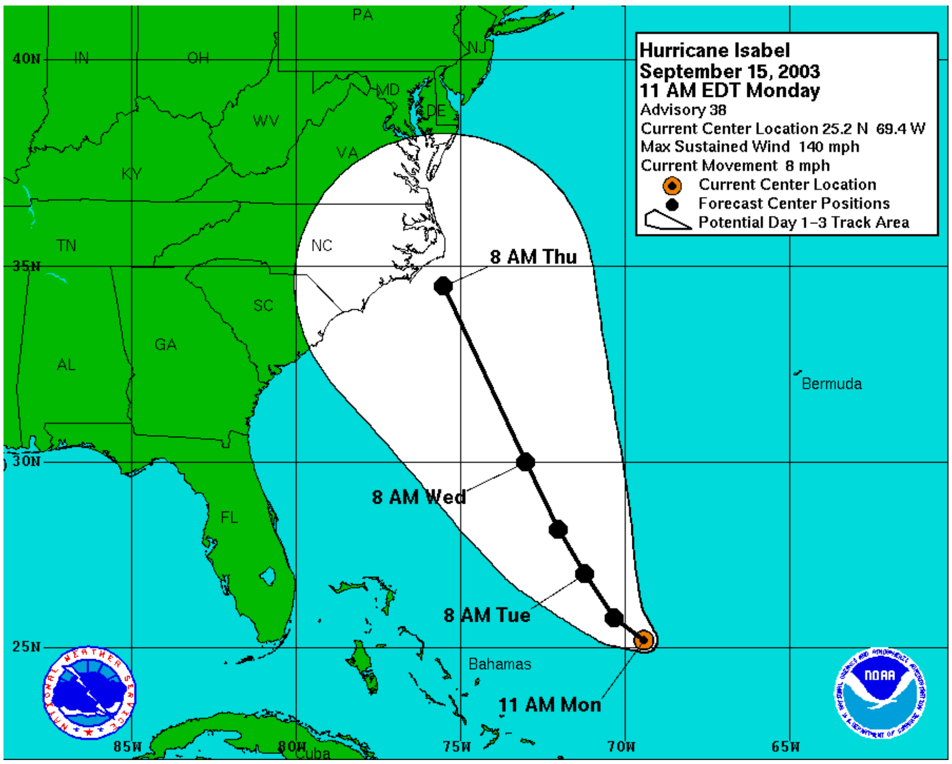

Figure 5. Hurricane Isabel, 2003 forecast image issued at 11AM EDT, 15 September, 2003 from National Weather Service

In the graphical forecast, the forecast position of the eye of the storm is indicated by the black circles and the line connecting those points is the forecast track of the eye of the storm, commonly referred to as the forecast track:

> NHC forecast tracks of the center can be in error; track forecast errors in recent years were used to construct the areas of uncertainty for the first 3 days (solid white area) and for days 4 and 5 (white stippled area). These areas of uncertainty are formed by enclosing the area swept out by a set of circles (not shown) along the forecast track (at 12, 24, 36 hours, etc). The size of each circle is set so that two-thirds of historical official forecast errors over a 5-year sample fall within the circle. The historical data

> indicate the entire 5-day path of the center of the tropical cyclone will remain within the outer uncertainty area about 60-70% of the time (National Weather Service, 2007c).

The white area around the track indicates a region within the mean historical distance from the official position forecasts. This white region is commonly referred to as the “error cone” and is created by connecting the error radii at the various forecast time intervals.

Along with the position forecasts, NHC publishes intensity forecasts to provide an estimate of the level of damage that a particular storm will cause so that the region where the tropical cyclone is forecast to go can adequately prepare. A new intensity probability forecasting product, NHC’s Surface Wind Speed Probabilities forecast was first issued in 2006 and is described by NHC as follows:

> The Tropical Cyclone Surface Wind Speed Probabilities text product provides probabilities, in percent, of sustained wind speeds equal to or exceeding 34-, 50-, and 64-knot wind speed thresholds. These wind speed probabilities are based on the track, intensity, and wind structure forecasts and uncertainties from the National Hurricane Center and the Central Pacific Hurricane Center and are computed for coastal and inland cities as well as offshore locations (e.g., buoys) (National Weather Service, 2007d).

Figure 6 is a NHC wind speed probabilities forecast for Tropical Storm Ernesto in 2006. The NHC produces forecast products that are aimed at providing the most information to the largest population with the goal of saving lives and minimizing property damage. In the Wind Speed Probabilities product, the NHC forecast only indicates the anticipated extent of winds in excess of 64 kts (and lower winds speed thresholds), which is not sufficient for the evacuation decision at ENCMCFI.

```
ZCZC MIAPWSAT5 ALL
TTAA00 KNHC DDHHMM
TROPICAL STORM ERNESTO WIND SPEED PROBABILITIES NUMBER  23
NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL   AL052006
0900 UTC WED AUG 30 2006

AT 0900Z THE CENTER OF TROPICAL STORM ERNESTO WAS LOCATED NEAR
LATITUDE 25.6 NORTH...LONGITUDE 80.9 WEST WITH MAXIMUM SUSTAINED
WINDS NEAR 40 KTS...45 MPH...75 KM/HR.

CHANCES OF SUSTAINED (1-MINUTE AVERAGE) WIND SPEEDS OF AT LEAST
   ...34 KT (39 MPH... 63 KPH)...
   ...50 KT (58 MPH... 93 KPH)...
   ...64 KT (74 MPH...119 KPH)...
FOR LOCATIONS AND TIME PERIODS DURING THE NEXT 5 DAYS

PROBABILITIES FOR LOCATIONS ARE GIVEN AS IP(CP) WHERE
    IP  IS THE PROBABILITY OF THE EVENT BEGINNING DURING
        AN INDIVIDUAL TIME PERIOD (INDIVIDUAL PROBABILITY)
   (CP) IS THE PROBABILITY OF THE EVENT OCCURRING BETWEEN
        06Z WED AND THE FORECAST HOUR (CUMULATIVE PROBABILITY)

PROBABILITIES ARE GIVEN IN PERCENT
X INDICATES PROBABILITIES LESS THAN 0.5 PERCENT
LOCATIONS SHOWN WHEN THEIR TOTAL CUMULATED 5-DAY
   PROBABILITY IS AT LEAST 2.5 PERCENT

Z INDICATES COORDINATED UNIVERSAL TIME (GREENWICH)
   ATLANTIC STANDARD TIME (AST)...SUBTRACT 4 HOURS FROM Z TIME
   EASTERN  DAYLIGHT TIME (EDT)...SUBTRACT 4 HOURS FROM Z TIME
   CENTRAL  DAYLIGHT TIME (CDT)...SUBTRACT 5 HOURS FROM Z TIME


  - - - - WIND SPEED PROBABILITIES FOR SELECTED  LOCATIONS - - - -

               FROM    FROM    FROM    FROM    FROM    FROM    FROM
  TIME       06Z WED 18Z WED 06Z THU 18Z THU 06Z FRI 06Z SAT 06Z SUN
PERIODS        TO      TO      TO      TO      TO      TO      TO
             18Z WED 06Z THU 18Z THU 06Z FRI 06Z SAT 06Z SUN 06Z MON

FORECAST HOUR    (12)   (24)    (36)    (48)    (72)    (96)   (120)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
LOCATION       KT

MOREHEAD CITY  34  X   X( X)   8( 8)  14(22)   7(29)   2(31)   X(31)
MOREHEAD CITY  50  X   X( X)   1( 1)   3( 4)   3( 7)   X( 7)   X( 7)
MOREHEAD CITY  64  X   X( X)   X( X)   1( 1)   1( 2)   1( 3)   X( 3)

WILMINGTON NC  34  X   1( 1)  13(14)  19(33)   6(39)   1(40)   X(40)
WILMINGTON NC  50  X   X( X)   2( 2)   4( 6)   4(10)   1(11)   X(11)
WILMINGTON NC  64  X   X( X)   X( X)   2( 2)   1( 3)   X( 3)   X( 3)

$$
FORECASTER STEWART

NNNN
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Figure 6. Hurricane Ernesto Wind Speed Probabilities forecast issued: 30 Aug, 2006 from National Hurricane Center

E. THESIS SCOPE AND PURPOSE

The following chapters develop a quantitative analysis of the decision to evacuate base personnel under the command of ENCMCFI. The factors that should influence that decision are examined by the analysis. This thesis is focused exclusively on preservation of human lives. While protecting property from damage is a consideration for base commanders, it is not the primary purpose of this thesis. Thus actions to prevent property damage are assumed to be implemented in a manner that will not affect the evacuation decision or timelines. The overall purpose of this thesis is to develop quantitative support for a base commander's evacuation decision. This thesis identifies what evacuation options are available based on storm dynamics. The key decision variables to this problem are:

- What size and intensity storm (at landfall) should initiate an evacuation?
- What does the forecast of that storm look like at lead times required to execute an evacuation? In particular, given a storm's current position and forecast, how much risk and variability are there in the forecast track and intensity forecast?
- Assuming that an evacuation is necessary, how many personnel and dependents should be sent to which evacuation destination by which mode of transportation (Commercial Bus, Air, Organic ground transport, etc…)?
- Additionally, as the storm comes closer, when do options begin to incur greater risk because they never become more costly to execute, and when are they no longer viable?

The thesis will also propose a model to estimate the probability of adverse impacts – which occur when winds reach 105 kts – at ENCMCFI for a threatening storm, based on its forecast. Local area building codes dictate that buildings should be built to withstand sustained winds of 105 kts, as discussed in Chapter II. The model use will be illustrated using historical data. Chapter II contains the methodology for the statistical tropical cyclone model and displays how probabilities of winds exceeding 105 kts at ENCMCFI are obtained.

Chapter III contains the decision model using the storm probabilities generated as described in Chapter II to compare direct costs and risk costs of evacuating versus

remaining. The decision model should give guidance on the best evacuation decision. Chapter IV is an analysis of historical tropical cyclones to illustrate the performance of the model. Chapter V contains conclusions and recommendations for further research.

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II. CALCULATING RISK TO ENCMCFI

When a tropical cyclone forecast indicates that a storm will come close to ENCMCFI, there is a need to assess the risk to ENCMCFI. The risk of winds 105 kts or greater occurring at ENCMCFI must be estimated. Three main variables that influence the probability of winds exceeding 105 kts at ENCMCFI: storm location (represented by its center, or estimated location of minimum pressure), storm intensity (measured by maximum wind speed) and the radius of maximum winds of the storm. The combination of extreme values in all three variables indicates that an evacuation is warranted. Forecast storm position is often misleading because it represents the tropical cyclone as a single point in space, and does not depend on the intensity or size of the storm. Even the current position of the storm is not exact. This position is an estimate of the center of the eye. This chapter describes the method to assess the effect of a current storm on ENCMCFI using historical storm information.

A. DATA

Atlantic Basin tropical cyclone forecast data and actual storm data from 1996-2005 are used to capture the variability in the storm location and intensity. The forecast data are recorded in a series of data files referred to as the A-Decks, which contain the official NHC forecast position and the forecast data from all of the weather models that go into the creation of the official forecast (National Weather Service, 2007a). During the course of a tropical cyclone, the NHC issues forecasts every six hours. These forecasts estimate the position of the storm at time periods 12, 24, 36, 48, 72, 96, 120 hours in the future. Let T_f be the set of forecast time periods: $T_f \in \{12, 24, 36, 48, 72, 96, 120\}$. For reasons that will be illustrated later in this chapter, there is a need to calculate storm parameters at intervals smaller than the forecast intervals. Let T_S be the set of intervals every 3 hours from 12 hours to 120 hours: $T_S \in \{12, 15, 18, ..., 117, 120\}$. After the Atlantic Hurricane season ends, the NHC

conducts a review of satellite data and issues a corrected “best track” which is disseminated in a dataset referred to at the B-Decks. The NHC defines “best track” as:

> A subjectively-smoothed representation of a tropical cyclone's location and intensity over its lifetime. The best track contains the cyclone's latitude, longitude, maximum sustained surface winds, and minimum sea-level pressure at 6-hourly intervals. Best track positions and intensities, which are based on a post-storm assessment of all available data, may differ from values contained in storm advisories. They also generally will not reflect the erratic motion implied by connecting individual center fix positions (National Weather Service, 2007b).

B. STORM POSITION ERROR

1. Position Error

The center of a tropical cyclone is the most commonly used forecast data point. It gives the most general storm effect information. Through the analysis of differences between NHC forecast position and the best track storm position for a given forecast lead time, it is possible to create historical error distributions about the forecast storm position. The error is the distance from the forecast position to the actual storm position at a given time. The forecast track is used as the direction of travel (decision makers at ENCMFCI will have only forecast information when they are making hurricane evacuation decisions).

2. Cross Track Error and Along Track Error

Positional errors of tropical cyclone forecasts are broken down into components: Cross Track Error (XTE) is the error perpendicular to the forecast track and Along Track Error (ATE) is the error parallel to the forecast track. These terms are commonly used to describe the difference between a forecast track and the actual course traveled. Elsberry and Peak (1986) state: “A prediction of a cross track component to the left or right of the present track is of considerable interest because of the different damage patterns to the left and right of the path. An increase or decrease in the forward displacement relative to a persistence forecast would assist in forecasting the time of storm passage.” In addition to storm forecasting, XTE and ATE are used in many navigational programs to provide

insight into position errors. As in marine navigation, the decomposition of absolute position errors into different components enables forecasting errors to be analyzed and exploited in more detail; in particular, biases can be computed. By relating the error to the track of the storm at a given time period, it is possible to represent the forecast error in relation to the storm better than using simple latitudinal and longitudinal direction errors. XTE has the biggest impact on where the storm will eventually go, and it may fall on either side of the forecast track. Positive XTE values indicate displacement to the right of the forecast track, and negative values indicate displacement to the left of the track. ATE affects the time a storm reaches a specified location. Figure 7 illustrates the method for calculating XTE and ATE. The XTE and ATE are calculated from one forecast time to the next forecast time.

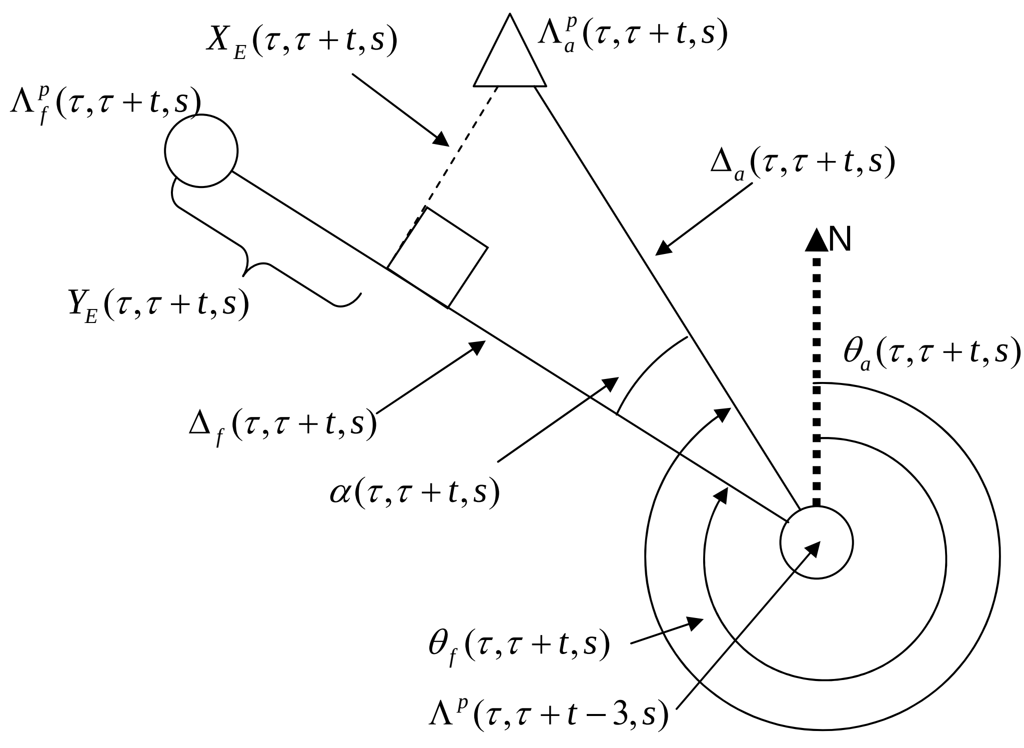

Figure 7. Illustration of XTE and ATE calculations

$\Lambda^p(\tau, \tau+t-3, s)$ = Position of storm s (actual position if $t=3,$ else forecast position) at $\tau+t-3$ based on forecast given at τ (Vector of latitude and longitude)

$\Lambda_a^p(\tau, \tau+t, s)$ = Actual position of storm s at $\tau+t$ (Vector of latitude and longitude)

$\Lambda_f^p(\tau, \tau+t, s)$ = Forecast position of storm s at $\tau+t$ based on forecast given at τ (Vector of latitude and longitude)

$\Delta_a(\tau, \tau+t, s)$ = Great circle distance between positions $\Lambda^p(\tau, \tau+t-3, s)$ and $\Lambda_a^p(\tau, \tau+t, s),$ calculated using Formula 2.1

$\Delta_f(\tau, \tau+t, s)$ = Great circle distance between positions $\Lambda^p(\tau, \tau+t-3, s)$ and $\Lambda_f^p(\tau, \tau+t, s),$ calculated using Formula 2.1

$\theta_a(\tau, \tau+t, s)$ = The bearing in degrees from magnetic North from $\Lambda^p(\tau, \tau+t-3, s)$ to $\Lambda_a^p(\tau, \tau+t, s)$ calculated using Formula 2.2

$\theta_f(\tau, \tau+t, s)$ = The bearing in degrees from magnetic North from $\Lambda^p(\tau, \tau+t-3, s)$ to $\Lambda_f^p(\tau, \tau+t, s)$ calculated using Formula 2.2

$\alpha(\tau, \tau+t, s)$ = The difference in bearing in degrees between $\theta_a(\tau, \tau+t, s)$ and $\theta_f(\tau, \tau+t, s),$ calculated using Formula 2.3

$X_E(\tau, \tau+t, s)$ = The XTE distance between $\Lambda^p(\tau, \tau+t-3, s)$ and $\Lambda_a^p(\tau, \tau+t, s),$ calculated using Formula 2.4

$Y_E(\tau, \tau+t, s)$ = The ATE distance between $\Lambda^p(\tau, \tau+t-3, s)$ and $\Lambda_a^p(\tau, \tau+t, s),$ calculated using Formula 2.5

The calculation of ATE involves the same variables as the calculation of XTE with a similar trigonometric relationship. If the storm traveled further than forecast, the ATE is positive; if the storm traveled less distance than forecast, the ATE is negative. In order to determine these error distances, the distance from the forecast position to the verifying storm position must be calculated. Since the earth is approximately spherical, simple two-dimensional trigonometric calculations will not provide accurate distance measures, especially at longer distances. Great circle distance calculations must be performed in order to accurately determine these distances. Equations 2.1 through 2.5 (Williams, 2006) are used to calculate XTE and ATE. The bearing between forecast and actual positions must also be calculated. These calculations are displayed in equations 2.2 and 2.3.

$$\text{Distance between positions } i \text{ and } j = r \times \cos^{-1}\left(\sin(lat_i)\times\sin(lat_j)+\cos(lat_i)\times\cos(lat_j)\times\cos(lon_i-lon_j)\right) \tag{2.1}$$

$$\text{Bearing between two points } i \text{ and } j = \tan^{-1}\left\{\frac{(lon_j - lon_i)}{(lat_j - lat_i)}\right\} \tag{2.2}$$

where $lat_i =$ the latitude of position *i*; $lon_i =$ the longitude of position *i*
$lat_j =$ the latitude of position *j*; $lon_j =$ the longitude of position *j*

$$\alpha(\tau,\tau+t,s) = \theta_f(\tau,\tau+t,s) - \theta_a(\tau,\tau+t,s) \tag{2.3}$$

$$X_E(\tau,\tau+t,s) = \Delta_f(\tau,\tau+t,s) \times \sin\left(\alpha(\tau,\tau+t,s)\right) \tag{2.4}$$

$$Y_E(\tau,\tau+t,s) = \Delta_f(\tau,\tau+t,s) \times \cos\left(\alpha(\tau,\tau+t,s)\right) \tag{2.5}$$

3. Storm Position Probability Distribution

To be useful in calculating the risk a given storm poses to ENCMFCI, the historical data must be organized to assess a conditional probability distribution for the future storm position given the storm forecast. Using historical Atlantic basin tropical cyclone data, the XTE and ATE are calculated for each historical forecast position for storms from 1996-2005 as described in Figure 7. The NHC forecasts the location of the storm's center to the nearest 0.1 degree; since one degree is approximately 60 nm, a maximum error of 6nm of error exists in each position estimate. Using this limitation in forecast fidelity as a basis, all of the forecast errors are placed into 6nm bins about the forecast position for each forecast time period. The errors are compiled into a master error matrix as depicted below in equations 2.6 and 2.7.

$$X_B(\tau,\tau+t,s) = \left\lfloor \frac{X_E(\tau,\tau+t,s)}{6} \right\rfloor \text{ if } X_E(\tau,\tau+t,s) < 0, \left\lceil \frac{X_E(\tau,\tau+t,s)}{6} \right\rceil \text{ otherwise} \tag{2.6}$$

$X_B(\tau,\tau+t,s) =$ The cross track bin calculated from actual storm position at $t+\tau$ to forecast storm position at $t+\tau$ based on forecast at τ, for storm *s*

where $\lfloor X \rfloor$ is the largest integer less than X, and $\lceil X \rceil$ is the smallest integer greater than X.

$$Y_B(\tau,\tau+t,s) = \left\lfloor \frac{Y_E(\tau,\tau+t,s)}{6} \right\rfloor \text{ if } Y_E(\tau,\tau+t,s) < 0, \left\lceil \frac{Y_E(\tau,\tau+t,s)}{6} \right\rceil \text{ otherwise} \tag{2.7}$$

$Y_B(\tau,\tau+t,s) =$ The along track bin calculated from actual storm position at $t+\tau$ to forecast storm position at $t+\tau$ based on forecast at τ, for storm *s*

For each value of $t \in T_F$, $X_B(\tau, \tau + t, s)$ and $Y_B(\tau, \tau + t, s)$ are calculated $\forall \tau, s$ and compiled to create an error matrix of actual storm errors about the forecast storm position for each time period $t \in T_F$. $X_B(\tau, \tau + t, s)$ and $Y_B(\tau, \tau + t, s)$ are the XTE and ATE error bin numbers for each historical forecast. This is a floor function if the error is negative (left of behind the forecast position), and is a ceiling function if the error is positive. Let M_P be the 3-dimensional matrix of observed joint frequency distribution of historical storm position errors, where $M_P(x, y, t)$ is the number of historical errors falling in XTE bin x and ATE bin y for a given $t \in T_F$.

C. STORM INTENSITY ERROR

The second parameter used in calculating the risk to ENCMFCI is the intensity of the storm. The NHC quantifies tropical cyclone intensity as the maximum 1-minute sustained wind speed (Landsea, 2006). This wind-speed is forecast by the NHC for the same time periods as the positions. While position error forecast accuracy has improved over time, errors in forecasting storm intensity still plague forecasters. Tropical cyclone intensity is an unpredictable feature of a storm. Hurricane Wilma in 2005 intensified from a rather benign 60 kts tropical storm into a 150 kts Category 5 hurricane in just 24 hours (National Hurricane Center, 2006b). The 24-hour forecast for this time period was 80 kts; the error was 70 kts. This lack of forecasting skill makes a historical perspective very valuable for decision makers at ENCMCFI. In the absence of other information, the question "What have other storms like this done in the past?" comes to the forefront. Intensity is especially important to ENCMCFI decision makers. The ability to safely shelter base occupants is compromised in storms with winds of 105 kts or more due to the engineering limits of the shelters. Current building codes for coastal North Carolina require that new buildings withstand a three-second wind gust of 130 kts which translates to a 105 kts sustained wind load (The Institute for Business and Home Safety, 2005). Wind speed is the driving factor in the tropical cyclone evacuation decision due to this vulnerability of local structures to extreme hurricane force winds.

Intensity data, much like the positional data, comes from the official NHC forecasts and post-season best track data. Intensity error is measured as the difference between the forecast storm intensity at a forecast period and the actual intensity from the best track data set. A storm whose intensity exceeds the forecast value has a positive error, and a storm whose intensity is below that of the forecast value has a negative error. Let: $\Lambda_a^i(\tau, \tau+t, s)$ be the actual intensity of storm *s* at $\tau+t$, and $\Lambda_f^i(\tau, \tau+t, s)$ be the forecast intensity of storm *s* at $\tau+t$ based on forecast given at τ. Time τ forecast intensity error for lead time t for storm $s = \Lambda_f^i(\tau, \tau+t, s) - \Lambda_a^i(\tau, \tau+t, s)$.

For each forecast time period, the frequency historical storm intensity errors (since forecasts are issued to the nearest 5 kts, errors are automatically binned) are calculated and stored in a matrix M_I for use in estimating the probability of a storm's winds exceeding 105 kts, given the forecast intensity, as discussed later in this chapter. Figure 8 displays an example of the resulting frequency distribution for a forecast time period of 48 hours, on a forecast of 90 kts. Note that the error distribution is centered about 90 kts. $M_I(w,t)$ is the observed frequency of historical storm intensity errors of *w* kts for lead time $t \in T_F$.

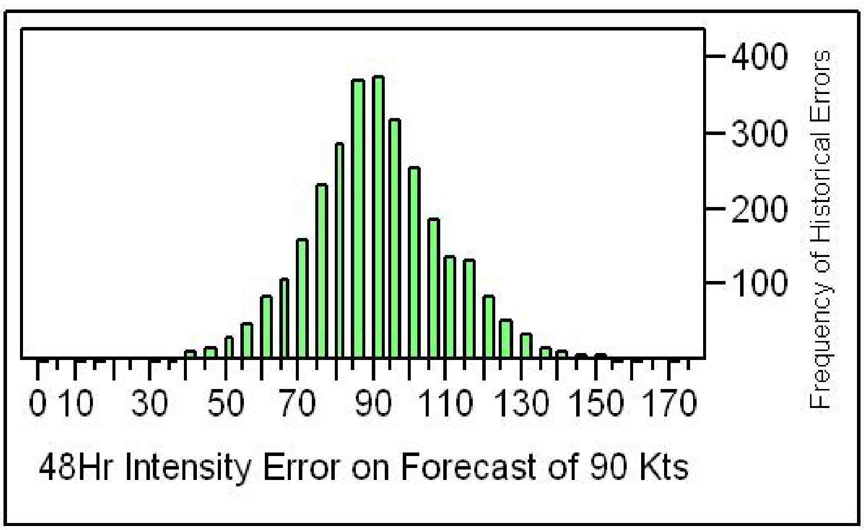

Figure 8. 48-Hr intensity frequency distribution from 1996-2005 Atlantic Tropical Cyclones (2977 Tropical Storms total), assuming a forecast of 90 kts.

D. STORM SIZE

The size of a tropical cyclone is another factor that influences whether a tropical cyclone affects ENCMCFI: "Hurricane winds can extend outward to about 25 miles from the storm center of a small hurricane and to more than 150 miles for a large one. The area over which tropical-storm force winds occur is even greater, ranging as far out as almost 300 miles from the eye of a large hurricane" (National Oceanic and Atmospheric Administration, 1999). While the swath of tropical-storm force winds can extend hundreds of miles, the maximum winds of the storm are located just outside of the eye wall of the tropical cyclone. The most intense winds occur in this narrow area. Thus locations near the eye of a storm passes suffer the worst effects of the storm. Size and intensity are not correlated: stronger storms are not necessarily bigger. In 2005, Hurricane Wilma had maximum winds of 160 kts and an eye of only 2nm in diameter before the eye then grew to a more typical size of 40nm-60nm in diameter. Hurricane Carla, in 1961, had a diameter of hurricane-force winds of 300 miles, and diameter of tropical-storm force winds of 500 miles (Weather Research Center, 2005).

To report a tropical cyclone's size, forecasters typically measure the radius of winds if a given speed. The radius of maximum winds, the radius of hurricane-force winds and the radius of tropical-storm force winds are the three most widely reported and measured. These size parameters are included in the A-decks and are broken down by quadrant of the storm to indicate any irregularity in the shape of a storm. Winds in a tropical cyclone are not symmetric, as is indicated by the wind-speed map for Hurricane Fabian, in 2003, shown in Figure 9. The strongest winds of tropical cyclones in the Atlantic Ocean are typically on the right side of the storm relative to the direction of travel. The direction of travel is indicated with an arrow in Figure 9. Accuracy in forecasting the shape of the wind-field inside of a tropical cyclone is very difficult to attain. The wind field will be treated as symmetric about the eye of the storm due to lack of reliable information about the wind speeds in each quadrant of a tropical cyclone.

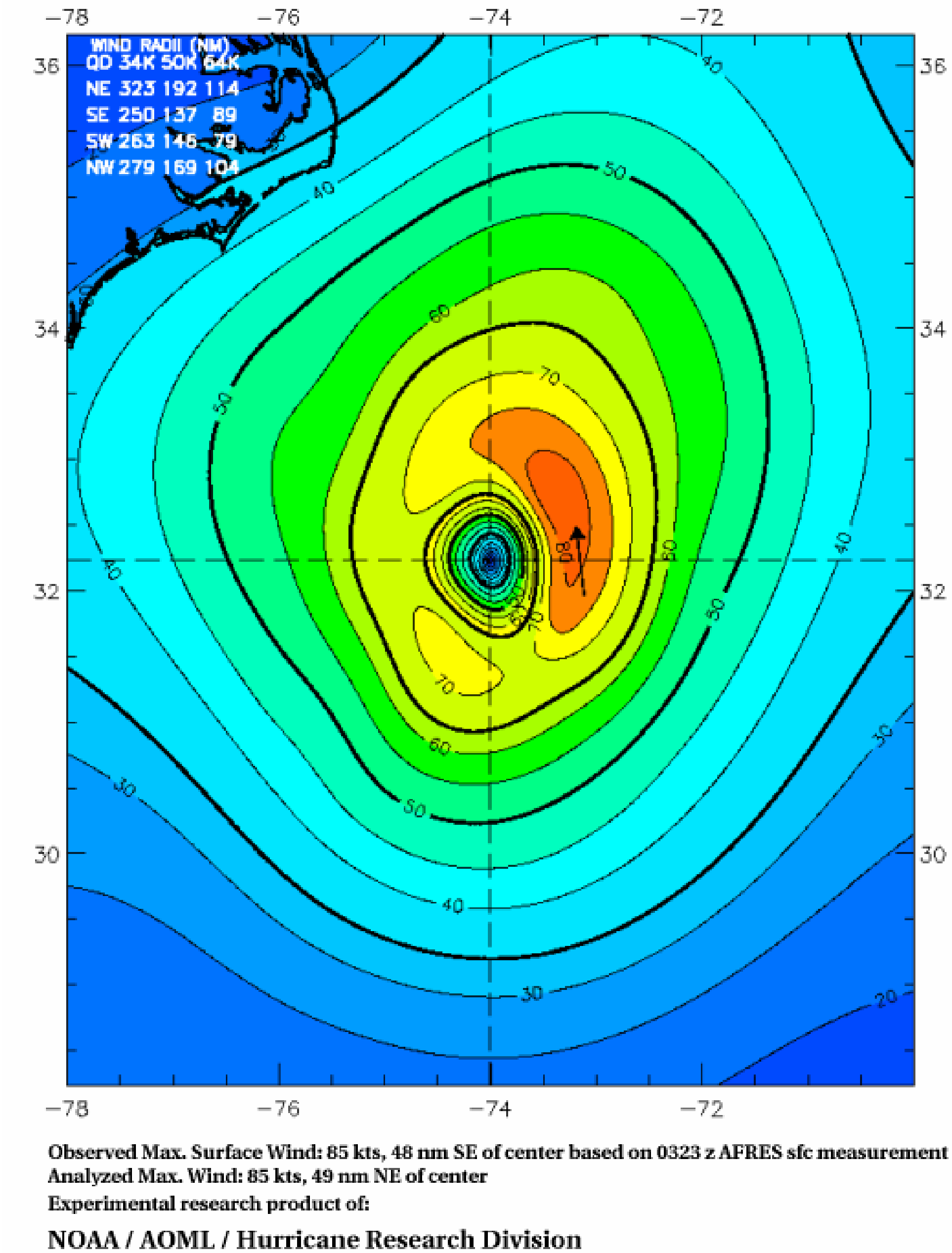

Figure 9. Windspeed isoquants (in kts) for Hurricane Fabian in 2003. Source: AMOL Hurricane Research Division website.(Atlantic Oceanic and Meteorological Laboratory 2007)

The two size parameters that really matter to decision makers at ENCMCFI are the radius of winds of at least 105 kts and the radius of tropical-storm force winds (i.e. at least 34 kts). The arrival of tropical storm force winds will put an end to evacuation operations. Base commanders consider moving personnel in tropical storm force winds

too dangerous. For storms with intensities of less than 105 kts, evacuation is not needed. For storms with intensities well above 105 kts, representing the size of the storm with either the radius of maximum winds or the radius of hurricane force winds is inadequate. Using the radius of maximum winds may underestimate the dangerous area of the storm, and may not prompt an evacuation when one is required. On the other hand, using the radius of hurricane-force winds (65 kts or greater) may overestimate the region of adverse conditions, and may erroneously indicate that an evacuation is warranted. Measures reported by NHC do not directly estimate probability of winds exceeding 105 kts at ENCMCFI. Thus another procedure to estimate the radius of winds in excess of 105 kts is considered.

Willoughby et al. (2006) propose a parametric procedure to determine the wind profile of a tropical cyclone. By using the maximum winds and latitude of the tropical cyclone, a sectionally continuous wind profile can be derived through the use of a power function and the sum of two exponential functions. Using equation 2.8, the radius of winds in excess of 105 kts (r for $V_0 = 105$) for a given storm are estimated with the forecast intensity as the value of V_{Max}. The other parameters are functions of V_{Max}.

$$V_O = V_{Max}\left[(1-A)\times\exp\left(-\frac{r-R_{Max}}{X_1}\right) + A\times\exp\left(-\frac{r-R_{Max}}{X_2}\right)\right] \tag{2.8}$$

$R_{Max} = 46.4\times\exp(-0.0155V_{Max} + 0.0169\varphi)$

$X_1 = 317.1 - 2.026V_{Max} - 1.915\varphi$

$n = 0.4067 + 0.0144V_{Max} - 0.0038\varphi$

$A = 0.0696 + 0.0049V_{Max} - 0.0064\varphi, (A \geq 0)$

V_{Max} = Maximum wind speed

φ= Latitude of hurricane, assumed to be fixed at 34.1N (Latitude for ENCMFCI)

r = Radius of tangential wind component

V_O = Wind speed of tangential wind component

The results of applying this formula to extrapolate the radius of winds in excess of 105 kts are depicted in Figure 10. According to the Willoughby (2006) model, 105 kts winds occur in a region from 19-24nm from the storm's center. This radius is estimated as 24nm for all storms with winds in excess of 105 kts in further calculations.

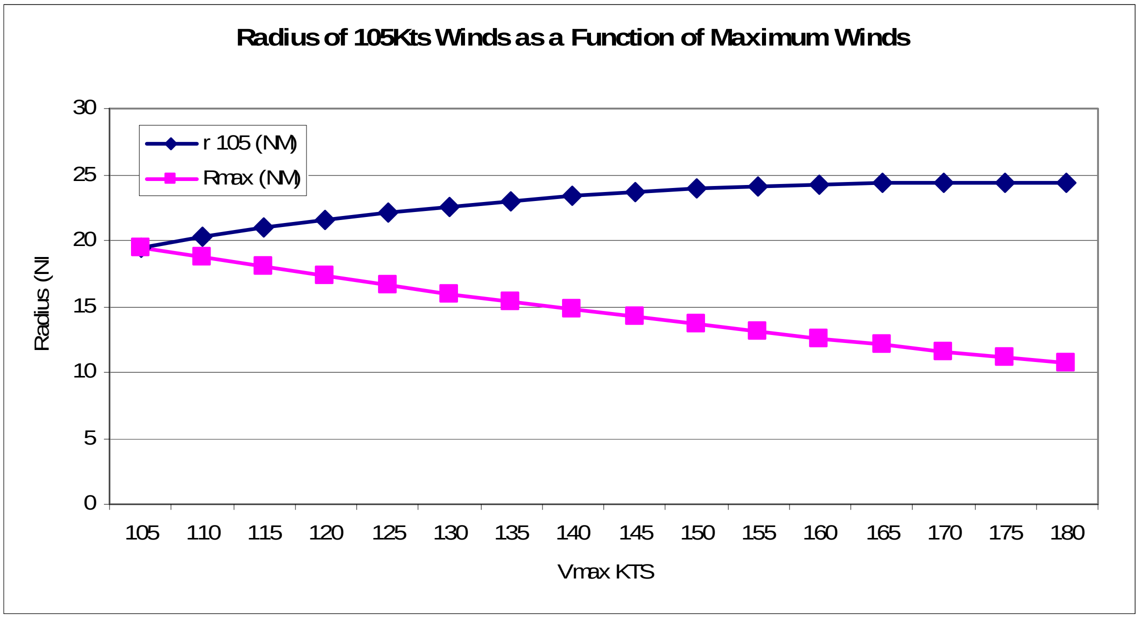

Figure 10. Application of Willoughby et al (2006) Formula estimating the radius of maximum winds and radius of 105 kts winds as a function of maximum wind speed.

This formulation does not apply to the estimation of the radius of tropical-storm force winds. The radius of these winds is an NHC forecast variable included in the official forecast. These values are issued for each quadrant due to the asymmetry of a storm's wind profile. The maximum single quadrant value for each forecast time period is used in further calculations.

E. INTERMEDIATE TIME POINT ESTIMATION

Given the distances that tropical cyclones can travel during a 12 or 24-hour forecast period, it is possible for a storm to affect ENCMCFI between forecast periods but not at either forecast point. In order to properly assess the potential risk, it is necessary to estimate the probability of winds affecting ENCMCFI between two observations. The errors in position increase approximately linearly as the forecast time period increases as is illustrated in Figure 11. Thus a weighted-average approach to estimating the values of the variables at intermediate time points is appropriate.

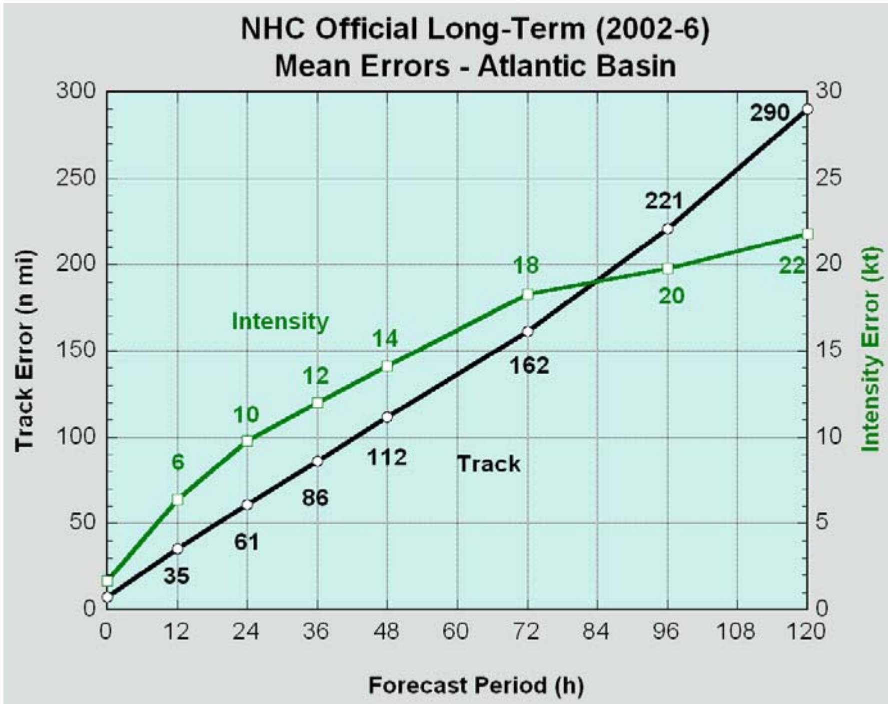

Figure 11. Mean Atlantic basin errors from 2002-2006 from Franklin (2007)

Intermediate time points have been modeled by creating error distributions for both position and intensity at three-hour intervals between the forecast time periods. Let T_S be the set of time points in the future for which storm probabilities are calculated, T_S: $\{12,15,18,\ldots,117,120\}$. The estimates at the intermediate points have been created by using a weighted average of the actual error matrices at times $t \in T_f$ above and below the intermediate point. The frequency of errors observed in each intermediate bin is the weighted average of the observed frequency in the bins for the time periods immediately above and below the intermediate point (Figure 12). Weights are proportional to the time from the intermediate point to the endpoints.

1	**1**	**1**
2	**2**	**1**
2	**4**	**3**
12 Hour		

1.5	1.25	1
2.5	2.5	1.25
2.75	4	3
15 Hour		
0.75x12Hr+ 0.25x24Hr		

2	1.5	1
3	3	1.5
3.5	4	3
18 Hour		
0.5x12Hr+ 0.5x24Hr		

2.5	1.75	1
3.5	3.5	1.75
4.25	4	3
21 Hour		
0.25x12Hr+ 0.75x24Hr		

3	**2**	**1**
4	**4**	**2**
5	**4**	**3**
24 Hour		

Figure 12. Illustration of intermediate point calculation procedure, showing a 3×3 section of the positional error matrix M_P, with values indicating the frequency of historical errors in each bin.

F. INTEGRATING THE POSITION, INTENSITY, AND STORM SIZE

When a forecast is issued by NHC, the forecast positions are input into the model. The cross track distance and along track distance to ENCMCFI are calculated from each forecast point at each forecast and intermediate time period. The track for this calculation is a straight line connecting the previous forecast position to the current forecast position. Let: $X_D^a(\tau, \tau+t)$ be the cross track distance (in nm) from forecast position at time $\tau+t$ to ENCMFCI based on time τ forecast and let: $Y_D^a(\tau, \tau+t)$ be the along track distance (in nm) from forecast position at time $\tau+t$ to ENCMFCI based on time τ forecast. To use this distance information with the master error matrix, the cross and along track distances must be transformed into their corresponding bins in the error matrix. Distances are divided by 6nm and the resulting normalized distances are assigned. Let $X_B^a(\tau, \tau+t)$ be the bin indicating the XTE that would put the storm at ENCMFCI at time $\tau+t$ based on time τ forecast:

$$X_B^a(\tau,\tau+t) = \left\lfloor \frac{X_D^a(\tau,\tau+t)}{6} \right\rfloor \text{ if } X_D^a(\tau,\tau+t) < 0, \left\lceil \frac{X_D^a(\tau,\tau+t)}{6} \right\rceil \text{ otherwise} \qquad (2.9)$$

x indexes XTE bins: $x \in Z, -250 \le x \le 250,\ x \ne 0$

Let: $Y_B^a(\tau, t+\tau)$ be the bin indicating ATE that would put storm at CLNC at time $t+\tau$ based on time τ forecast:

$$Y_B^a(\tau,\tau+t) = \left\lfloor \frac{Y_D^a(\tau,\tau+t)}{6} \right\rfloor \text{ if } Y_D^a(\tau,\tau+t) < 0, \left\lceil \frac{Y_D^a(\tau,\tau+t)}{6} \right\rceil \text{ otherwise} \qquad (2.10)$$

y indexes ATE bins: $y \in Z, -250 \le y \le 250,\ y \ne 0$

To generate an estimate of the probability that the center of the storm is in a position that would bring winds 105 kts or greater to ENCMCFI, the radius of maximum winds must be considered in the model as well as the size of the ENCMCFI complex. ENCMCFI cannot be viewed as a single point since the three major bases that make up the greater ENCMCFI area are over 30nm apart at their most distant points. Since a single evacuation decision is being made for the entire base complex, the eye passing within a certain distance of any point in this area is considered grounds for evacuation. The relevant distance from the eye is equal to the radius of winds (24nm) in excess of 105 kts estimated using equation 2.8. Combining the radius of winds with the size of the ENCMCFI complex produces a box of approximately 78nm square, which translates to thirteen 6nm bins per side of the square. The square is offset to the left (seven bins to the left and six to the right) due to the asymmetry shown in Figure 9. Estimating the probability that the eye causes winds in excess of 105 kts requires the fraction of historical storm position errors for the forecast time period that would put the storm inside the box surrounding ENCMCFI (equation 2.11). Let $\rho_{105}^{\text{Strike}}(\tau,\tau+t)$ be the estimated probability that the storm's center will be within 24nm of ENCMFCI at time $\tau+t$ based on forecast at τ :

$$\rho_{105}^{\text{Strike}}(\tau,\tau+t) = \left. \sum_{x=X_B^a(\tau,\tau+t)-7}^{X_B^a(\tau,\tau+t)+6} \sum_{y=Y_B^a(\tau,\tau+t)-7}^{Y_B^a(\tau,\tau+t)+6} M_P(x,y,t) \middle/ \sum_{x=-250}^{250} \sum_{y=-250}^{250} M_P(x,y,t) \right. \qquad (2.11)$$

The estimate of the probability that the storm's intensity will exceed 105 kts at a time step is calculated using the vector of historical intensity errors, $M_I(w,t)$, for the forecast time period *t*. The difference between the current forecast intensity and 105 kts is calculated. This error is compared to the values in the error matrix. The estimated probability of intensity error exceeding this difference is the frequency of errors that would produce intensity of 105 kts or greater:

$\rho_{105}^{Int}(\tau,\tau+t)$ = the fraction of historical storm intensity forecast errors for time period *t* that would make actual intensity at time $t+\tau$ $\geq$ 105 kts based on forecast at τ .

$$\rho_{105}^{\text{Int}}(\tau,\tau+t)= \sum_{w\geq 105-\Lambda_f^i(\tau,\tau+t)} M_I(w,t) \Big/ \sum_w M_I(w,t) \qquad (2.12)$$

The overall estimated probability of winds exceeding 105 kts at ENCMCFI at a given time period is calculated by equation 2.13 and is the product of the estimated strike probability and the estimated intensity probability. The probability distribution of a storm's position relative to ENCMCFI is assumed to be independent of the storm's intensity:

$$\rho_{105}(\tau,\tau+t)=\rho_{105}^{\text{Strike}}(\tau,\tau+t)\times\rho_{105}^{\text{Int}}(\tau,\tau+t) \qquad (2.13)$$

Another variable that must be considered is the estimated probability that winds will exceed 34 kts for a given time period. This event would cause evacuation operations to cease (discussed further in Chapter III). This calculation is conducted in much the same manner as the probability of winds of 105 kts or greater, except that the NHC forecasts the radius of winds for the 34 kts level. The probability of winds exceeding 34 kts at ENCMCFI is calculated using equation 2.14. Let $\rho_{34}(\tau,\tau+t)$ be the fraction of historical storm positions that are within $R(\tau,\tau+t)$ nm of ENCMCFI at time $\tau+t$ based on forecast at τ determined using XTEs and ATEs. Additionally let: $R(\tau,\tau+t)$ be the radius of tropical storm force winds at time $\tau+t$ based on forecast at τ. A conversion of the distance of $R(\tau,\tau+t)$ into bins, is displayed in equation 2.14.

$$R_B(\tau,\tau+t)=\left\lceil \frac{R(\tau,\tau+t)}{6} \right\rceil \qquad (2.14)$$

r indexes R bins: $r\in Z$, $0<r\leq 250$

$$\rho_{34}(\tau,\tau+t)=\frac{\displaystyle\sum_{x=X_B^a(\tau,\tau+t)-R_B(\tau,t+\tau)}^{X_B^a(\tau,\tau+t)+R_B(\tau,t+\tau)}\ \sum_{y=Y_B^a(\tau,\tau+t)-R_B(\tau,t+\tau)}^{Y_B^a(\tau,\tau+t)+R_B(\tau,t+\tau)} M_P(x,y,t)}{\displaystyle\sum_{x=-250}^{250}\sum_{y=-250}^{250} M_P(x,y,t)} \qquad (2.15)$$

The probability of winds exceeding either 105 kts or 34 kts in a given time period is a function not only of the storm forecast, but also of the time period duration. The probability of 34 kts winds arriving before evacuation operations are complete must be quantified to describe the risk of delaying evacuation operations. Let $W(\tau+t)$ be the maximum wind speed at ENCMCFI at time $\tau+t$. This is a random variable at the decision time τ. Its probability distribution is a function of the time τ forecast. Evacuation decisions will be made soon after the release of tropical cyclone forecasts by NHC. For the evacuation decision, the most important event is winds exceeding 105 kts at ENCMCFI at any point over the entire duration of the storm. Since NHC only issues forecasts out to 120 hours, this is the farthest in the future that it is possible to estimate the probability of a given storm impacting ENCMCFI. Thus the result that we are interested in is:

$$P\left[W(\tau+12)\geq 105 \cup W(\tau+15)\geq 105 \cup W(\tau+18)\geq 105 \cup \ldots \cup W(\tau+120)\geq 105\right] \quad (2.16)$$

$P\left[W(\tau+t)\geq 105\right]$ for a given t can be estimated as $\rho_{105}\left(\tau,\tau+t\right)$, as displayed in equation 2.13. The events of 105 kts winds at ENCMFCI at different times are assumed to be conditionally independent given the forecasts of positions and intensities at those times. Thus an estimate of:

$P\left[W(\tau+12)\geq 105 \cup W(\tau+15)\geq 105 \cup W(\tau+18)\geq 105 \cup \ldots \cup W(\tau+120)\geq 105\right]$ can be calculated using equation (2.17).

$$P\left[W(\tau+12)\geq 105 \cup \ldots \cup W(\tau+120)\geq 105\right] = 1-\left[\prod_{t\in T_S}\left(1-\left(\rho_{105}(\tau,\tau+t)\right)\right)\right] \quad (2.17)$$

Similarly, the probability of tropical storm force winds arriving at ENCMCFI must be evaluated over different time periods. While winds that exceed 105 kts at any time is a decision factor for evacuation, the arrival of tropical storm force winds is only a factor if it occurs while tropical cyclone evacuation operations are underway. This may be the determining factor for the evacuation decision because it represents the time at which the ability to evacuate will be lost for the duration of the storm. Similar to the discussion above, $P\left[W(\tau+t)\geq 34\right]$ for a given t can be estimated by $\rho_{34}(\tau,\tau+t)$. The

events of tropical storm force winds at ENCMCFI at different times are assumed to be conditionally independent given the forecasted positions of the storm and its forecasted intensities. The estimated probability of tropical storm force winds occurring at ENCMCFI over a specific time period is given by equation 2.18 where ψ is the last time period in the future for which the tropical storm force wind probability is relevant.

$$P\left[W(\tau+12)\geq 34\cup\ldots\cup W(\tau+\Psi)\geq 34\right]=1-\left[\prod_{\substack{t\in T_S\\ 12\leq t\leq\psi}}\left(1-\left(\rho_{34}(\tau,\tau+t)\right)\right)\right] \tag{2.18}$$

Equations 2.17 and 2.18 will perform an important role in the overall decision problem which will be addressed in the next chapter.

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III. DECISION PROBLEM FOR ENCMCFI

> Do you want to have 100% chance that two people will die, or a 2% chance that 100 people will die? -
>
> Dr. Eva Regnier, December 9, 2006

Forecasting the storm is only half of the greater problem of whether or not to evacuate in the face of an approaching storm. NHC forecast accuracy improves as lead time decreases. Thus, the decision becomes whether to evacuate now or wait for possibly more reliable information in the forecast that will be issued six hours later. The evacuation decision must be made before arrival of tropical-storm force winds. Evacuation operations cannot occur in tropical-storm force winds. The risk of evacuation is measured both in terms of monetary cost and expected number of fatalities. The risks include both direct costs and the risk of casualties associated with evacuation, and the costs due to casualties to those personnel who might remain in the area during a major hurricane. The costs involved are well documented direct evacuation costs incurred for travel and per-diem (lodging and meals for those evacuated) as well as less tangible costs of casualties. The uncertainties in the prediction of wind speeds and the risk of casualties make this decision complex. This chapter describes the framework for a model that includes these costs (both direct expenditures and monetized risks of casualties), in a single equation to identify when an evacuation should be ordered.

A. THE JUSTIFICATION FOR EVACUATING

All ENCMCFI personnel unable to evacuate will be forced to experience any storm effects that the area endures. The structures aboard ENCMCFI designated as hurricane evacuation shelters are rated to withstand only up to 105 kts of sustained winds (U.S. Marine Corps, Eastern North Carolina Marine Corps Forces and Installations, 2005).

1. Local Shelters

According to the destructive weather order currently in effect at ENCMCFI:

> Past and current building codes have not required buildings on Marine Corps Base, Camp Lejeune to be designed for winds exceeding 110 to 120 MPH [95 kts to 105 kts] Design criteria applied to current shelters, new schools, and other new construction does not include special provisions for winds above 120MPH [105 kts] (U.S. Marine Corps, Eastern North Carolina Marine Corps Forces and Installations, 2005).

This design limitation drives the decision to evacuate in the face of a Category-3 or higher hurricane. The buildings designated as hurricane shelters, are limited in capacity and thus the entire population of ENCMCFI cannot be safely sheltered on base. Personnel residing on the bases of ENCMCFI would have priority access to on-base shelters. Municipal shelters would serve personnel living off base. Base residential houses are rated to only 100mph [83 kts]. The majority of personnel at the base who do not evacuate will be sheltered in the strongest buildings on base.

The internal dynamics of tropical cyclones are impossible to predict reliably. It is possible for Category-2 storms to have localized winds in excess of 105 kts in some area(s) for short periods of time. Since the internal dynamics of a tropical cyclone are not forecasted, it is not possible to accurately estimate structural damage of individual buildings. The most likely scenario during a hurricane is that there will bea small number of buildings with many people in them resulting in a high risk for widespread casualties in the event of a shelter collapse.

2. Storm-Related Casualty Estimation

a. Estimation of the Number of Storm-Related Casualties

Assuming that some personnel remain at ENCMCFI, estimating the number of casualties during a particular storm is especially hard since there is no succinct historical dataset that captures storm-related casualties. Using historical data collected from U.S. Army Corps of Engineers (USACE) Hurricane Evacuation Study reports, and from National Oceanic and Atmospheric Administration (NOAA) Storm Reports, the

number fatalities that occurred during previous hurricanes can be determined by county. Based on these data, future losses are estimated as a percentage of the number of personnel that remain in the area where a hurricane comes ashore. Three major tropical cyclones whose effects were primarily wind related are identified in Table 2 and the number of fatalities in the counties directly affected by the hurricane landfall is compared to the population of that county (adjusted by the estimated evacuation rate) at that time. The evacuation rate is the estimated fraction of the population that evacuated. The fatality rate for those personnel who do not evacuate is estimated as 0.0049%.

Year	Storm	Category	Pop Remain	Death Rate:	Population[1]	Evac. Rate	Fatalities
1989	Hugo	4	73,790	0.00012197	295,159	0.75[2]	9[3]
1992	Andrew	4	1,181,308	0.00001270	3,192,725	0.63[4]	15[5]
2004	Charley	4	464,500	0.00001722	725,782	0.36[6]	8[7]
			Average:	0.000049			

Table 2. Recent major storm fatalities in coastal regions.

Data obtained from the Morbidity and Mortality Reports published by the Centers for Disease Control (CDC) are used to estimate the expected number of injuries in the population of personnel who ride out a major hurricane at ENCMCFI. This

[1] U.S. Census Bureau, (2004 Aug 5). Time Series of Intercensal Estimates by County. Retrieved May 22, 2007, from U.S. Census Bureau Web site: http://www.census.gov/popest/archives/2000s/vintage_2001/CO-EST2001-12/CO-EST2001-12.html.

[2] U.S. Army Corps of Engineers. (1990). *Hurricane Hugo Assessment Review of Hurricane Evacuation Studies Utilization and Information Dissemination* Tallahassee:

[3] National Atmospheric and Oceanic Administration. (1989). *September 1989 Storm Data* (ISSN 0039-1972). Washington D.C.: Retrieved on May 22, 2007 from NOAA Website: http://www1.ncdc.noaa.gov/pub/orders/BED14711-1190-3DE3-DD7E-2D2958A1939D.PDF.

[4] U.S. Army Corps of Engineers. (1993). *Hurricane Andrew Assessment - Florida Review of Hurricane Evacuation Studies Utilization and Information Dissemination* Tallahassee:

[5] National Atmospheric and Oceanic Administration. (1992). *August 1992 Storm Data* (ISSN 0039-1972). Washington D.C.: Retrieved on May 22, 2007 from NOAA Website: http://www1.ncdc.noaa.gov/pub/orders/BED14711-1190-3DE3-DD7E-2D2958A1939D.PDF.

[6] McCarty, C (2005).Florida's 2004 hurricane season: local effects. *Florida Focus*. *1*, 1-13.

[7] National Atmospheric and Oceanic Administration. (2005). *September 2005 Storm Data* (ISSN 0039-1972). Washington D.C.: Retrieved on May 22, 2007 from NOAA Website: http://www1.ncdc.noaa.gov/pub/orders/BED14711-1190-3DE3-DD7E-2D2958A1939D.PDF.

information is compiled based on reports from hospital emergency departments in different regions of the country which provide only general information to causes of the injuries. There is no clear data correlating injuries to specific causes (i.e. from windborne storm effects) as there are for the storms used for the creation of the fatality rate. Using the injury information from the CDC, the Multi-hazard Mitigation Council (a council of the National Institute of Building Sciences) has estimated the expected injury rate from a hurricane at 0.55% (National Institute of Building Science, 2005). This value is used to estimate injury rates for personnel who remain on base during a hurricane.

b. Casualty Cost Methodology

In order to combine direct expenses incurred in evacuating personnel with the risks of casualties, monetized values for deaths and injuries are needed. The monetized value (cost) of each casualty was produced using information from the Department of Defense instruction 6055.7, Accident Investigation, Reporting and Record Keeping (U.S. Department of Defense, 2000). The information in the instruction was computed in 1988. Table 3 displays the computation methodology, with figures adjusted for inflation. The costs per person are different across personnel categories. It is assumed that injuries and fatalities will occur in the same proportion represented in the general population; therefore, the costs are estimated to be a weighted average of the values across personnel categories. Injuries are assumed to result in permanent partial disability. The fatality cost is the cost from the instruction plus the cost of life insurance. Based on the data in Table 3, an injury to a person is estimated to cost $257,000 and a fatality is estimated to cost $625,000.

Population	Population Size	% of Total Population	Permanent Partial Disability Cost	Fatality Cost
Officers	4729	4.79%	$248,000.00	$1,076,000.00
Enlisted	47473	48.11%	$197,000.00	$614,000.00
Civilian Employees	4019	4.07%	$428,000.00	$887,000.00
Dependents	42457	43.03%	$308,000.00	$562,000.00
Total:	98678	Weighted Average:	$256,611.01	$624,886.12

Table 3. Casualty cost estimation values from U.S. Department of Defense Instruction 6055.7 and calculation of population-weighted average costs per person

3. Storm Aftermath

After the hurricane moves out of the area, additional costs are incurred by personnel who ride out the storm aboard ENCMCFI. Historically, in the aftermath of large hurricanes in southeastern North Carolina, the Cape Fear River and the Neuse River flood. The flooding places the extreme eastern part of North Carolina on an island. Many roads into the area are cut off. Delivering relief supplies and infrastructure repair capabilities into the region becomes extremely difficult, until the coastal flooding diminishes. After Hurricane Floyd in 1999, many rivers inland did not crest for 4-6 days after the storm (U.S. Department of Commerce, 2000). Based on this fact, the duration of the storm aftermath period will be estimated to be five days. This value is chosen because ENCMCFI is not located in the areas that experienced the worst flooding after Hurricane Floyd. The Marine Corps is uniquely equipped to be self-sustaining. Marine units have the capability to make clean water, to establish and maintain global secure communications and to feed large numbers of personnel. These resources are assumed to be used in hurricane response. It is assumed that damage to local infrastructure, specifically power supply, will prevent base dining facilities from operating. The cost per day of supporting a person in the storm's aftermath is estimated by the cost of placing a Marine on "Field Rations". Field Rations is the Marine Corps term for government provided meals in the field. This cost will be applied to both Marines and dependents that remain in the area.

4. Storm Risk Costs

Using the information outlined in this section, it becomes possible to estimate the cost of personnel remaining behind during a major storm. To compare to direct costs, costs must be assigned to fatalities and injuries that personnel at ENCMCFI incur during a major hurricane. A fatality or injury to a Marine or dependent that could have been evacuated from the area incurs a financial cost for medical expenses, life insurance claims, and in the case of an Active Duty Marine, replacing that Marine. These costs are summarized in Table 3. In addition, there are non-financial costs to the family and the

Marine Corps for the loss of life. To account for these non-financial costs, a penalty cost for storm related injuries and fatalities may be assessed. A sensitivity analysis is conducted with respect to the monetized cost of deaths.

B. THE EVACUATION PROBLEM

ENCMCFI is faced with a difficult problem when it comes to tropical-cyclone evacuation decisions. In addition to the need to leave the local area to avoid the most intense effects of the storm, an inland safe haven capable of withstanding significant wind effects and safely supporting a large number of people must be identified:

> After hurricane Hugo in North Carolina and Andrew in south Florida it became apparent that storm surge was not the only life-threatening feature of hurricanes. Destructive hurricane force winds and tornadoes affected many inland counties as far as 100 miles from the coast (USACE, 2002).

This need to find inland evacuation destinations coupled with the number of personnel and dependents that are stationed at ENCMCFI make this a decision problem of enormous magnitude. Sites have been chosen in North Carolina and South Carolina to house evacuees from ENCMCFI. The ENCMCFI population can be broken down into three blocks for the purposes of evacuation. Let *b* index the personnel blocks:

$$b=\begin{cases}1\text{: Personnel requiring Long Evacuation}\\ 2\text{: Personnel requiring Short Evacuation}\\ 3\text{: Self Evacuation Population}\end{cases}$$

The evacuations of blocks one and two are competing for the same assets and thus decisions regarding their evacuation are connected. The Self evacuation population uses their own transportation assets. The evacuation decision for this group is independent of the block one and two decisions.

Let $R(b,t)$ be the number of personnel in block *b* that remain at ENCMCFI at time *t*. The initial number of personnel at ENCMCFI when a hurricane threatens is represented by $R_M^0(0) = R(1,0) + R(2,0) + R(3,0)$. Let $R_M(\tau, \tau + s)$ be the number of personnel remaining at ENCMCFI if no further evacuations occur after time $\tau + s$ and

the evacuation starts at time τ. Let $H(b,t)$ be the number of personnel in each block b that are evacuated from ENCMCFI at time *t*. As an evacuation progresses the number of personnel from each block at ENCMCFI will decrease, as is illustrated in equation (3.1).

$$R(b,\tau) = R(b,0) - \sum_{t<\tau} H(b,t) \tag{3.1}$$

All values in this section come from products developed by LtCol Dewald, the Deputy Director for Training and Operations for ENCMCFI. All of these values are based on actual data collected from ENCMCFI. The population at ENCMCFI is a fluid one due to troop rotations and personnel assignments, so the actual values when a hurricane threatens may be slightly different (E. Dewald, Deputy Director for Training and Operations, ENCMCFI, 2006).

1. Personnel Blocks

a. Long Evacuation: Students, Prisoners and Special Needs

A large student population is assigned to ENCMCFI, for primary military training following recruit training. These students are not allowed to have personal vehicles. They must be positively moved by the government in the course of an evacuation. Approximately 5,500 students are present at ENCMCFI during the hurricane season. Approximately 450 support staff that will evacuate with the students. Grouped in the same block are approximately 250 short and medium-term prisoners incarcerated at Camp Lejeune. These personnel, along with their support staff, would be positively moved in the course of an evacuation. All of the members of this block (6,200 in total) are scheduled to evacuate to Ft Jackson in Columbia, S.C.

Some families of service members are unable to evacuate themselves. This block is comprised almost totally of dependents of active duty service members who do not have the means to evacuate themselves in the face of an impending storm. This population is very fluid and will depend on deployment cycles among other factors. ENCMCFI estimated the size of this population to be approximately 1,300. All of these

personnel must be positively moved, and are scheduled to evacuate to Shaw Air Force Base in Sumter, S.C. The distance from ENCMCFI to the long evacuation destinations is approximately 225 miles. With no delay the one-way travel time is approximately 5 hours in government vehicles.

The evacuation costs and time required are essentially identical for evacuation to Ft Jackson and Shaw Air Force Base. Therefore, the 6,200 students and prisoners and the 1,300 dependents are grouped together in block 1, for a total of $R(1,0) = 7{,}500$.

b. Short Evacuation: Deployed Warfighting Capability, Alternate Headquarters and Immediate Reentry Capability

As a member of the U.S. National Defense structure, ENCMCFI has responsibilities to the National Command Authority to maintain a force in readiness that is able to deploy on short notice. Members of this rapidly deployable unit must be mustered at least daily. Additionally, Marines scheduled to deploy overseas within 30 days would be evacuated with this block of personnel to ensure that troop rotations occur on time. The number in this block averages 2,500 Marines (one reinforced battalion). Due to rotation cycles in global conflicts this number may vary from 2,500-9,500 personnel. One thousand members of an alternate command headquarters will evacuate with this block to enable continuity of command. This group is scheduled to evacuate to Ft Bragg, N.C.

In the event of a total base evacuation, a 350-member immediate re-entry unit will be evacuated to Seymour Johnson Air Force Base to be the first personnel to return to ENCMCFI immediately following the storm. This block is comprised mostly of engineers and heavy-machinery operators who will facilitate re-opening of ENCMCFI.

Since Ft Bragg and Seymour Johnson Air Force Base evacuations are essentially the same cost and driving time from ENCMCFI, all these groups are combined for a total of: $R(2,0) = 3{,}850$. The distance from ENCMCFI to Ft Bragg is approximately 100 miles. With no traffic delay, a one way trip takes approximately two hours.

c. *Released Personnel*

The vast majority of personnel at ENCMCFI will be released at least 24 hours prior to storm landfall to evacuate themselves to the destination of their choosing. This population size is approximately $R(3,0) =$ 90,000 service members, dependents and civilian employees. This population is expected to have their own means of transportation, and will receive mileage reimbursement based on rates from the Joint Federal Travel Regulation (JFTR). Base commanders will direct those Marines who are not married to car-pool. One vehicle per every 3 people is assumed.

2. Transportation

Even though the vast majority of the base population is expected to move themselves in the course of an evacuation, there are expected to be approximately $R(1,0)+R(2,0)$ = 11,350 and possibly up to 18,000 personnel who require transportation to their designated evacuation site. ENCMCFI has a limited number of organic assets available to move these personnel, but has the capability to execute multiple trips. The use of commercial assets such as buses, to evacuate ENCMCFI personnel is not a reliable option (as discussed later). With the assets that are currently available, three round trips are required to move the entirety of the positive move population.

a. *Transportation Travel Time*

Because the base is required to execute multiple trips using its organic assets, the time it takes to make these trips becomes a critical planning factor. As a storm grows closer, however, the local population will begin to evacuate the area. This evacuation traffic increases the time for ENCMCFI assets to make these round trips. The USACE has developed "Clearance Time," a metric which has been estimated based on studies of past hurricane evacuations. The estimated metrics are updated and maintained by the USACE through their "Hurricane Evacuation Study" program.

> Clearance Time: the time required to clear the roadways of all evacuating vehicles. It therefore determines the minimum time period, in hours to the arrival of sustained 34-knot winds, necessary for a safe evacuation.

> Clearance times are based on three variables: 1) Saffir/Simpson hurricane category; 2) expected evacuee response rate; and 3) tourist occupancy situation (where applicable) (USACE, 2002).

These values represent clearance of the entire roadway not just the time estimated for one vehicle to move through the system. These times are not static, and they vary through a range based on the response rate:

> Another critical behavioral aspect of the transportation analysis is the response rate (timing) of the evacuating population. Behavioral data shows that actual departures of the evacuating population can occur over a period of many hours, or sometimes in a few hours. For this study, clearance times were tested for three evacuation response rates (slow, medium and fast) (USACE, 2002).

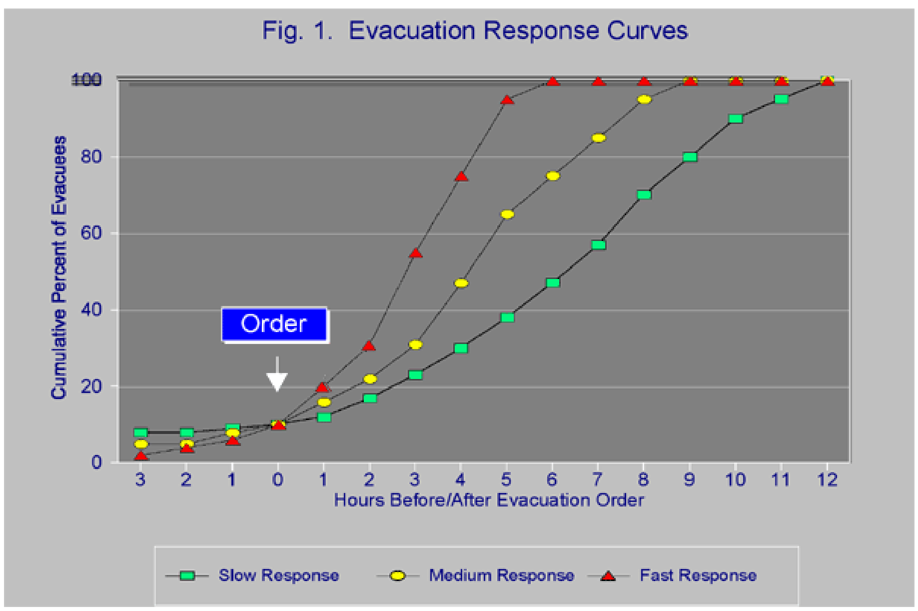

Figure 13. Graph displaying the effects of different response rates on the evacuation clearance times. From USACE, Hurricane Evacuation Study.

The effect of clearance times on the ability for ENCMCFI to maximize use of transportation assets is important. Table 4 displays clearance times for the counties where ENCMCFI installations are located. These times are the total clearance times for the entire county population to clear the road network to the I-95 corridor. The values for Pamlico South include locations on barrier islands that depend on ferries to complete their evacuation. These locations do not include members of the ENCMCFI population.

	Response Rate	CAT 1-2 (hours)	CAT 3-5 (hours)
Onslow County	rapid	8.5	10.5
	medium	9.5	11.25
	long	12.25	12.5
Pamlico South	rapid	12.25	18.5
	medium	13.25	19.75
	long	14.5	20.75
Pender County	rapid	4.75	6
	medium	6.25	6.5
	long	9.25	9.25

Table 4. ENCMCFI county clearance times in hours from USACE HES (2002)

While the clearance times provide insight, the value that is most important to this decision problem is the maximum "Worst Household Commute Time". This value is the maximum time that one vehicle could expect to spend getting through the road network. For the counties involved the estimate is 3 to 7.5 hours (USACE 2002). Since the long evacuation travel time was estimated at 5 hours without traffic delays, the trip to the destination takes between 8 and 12.5 hours one way with evacuation-related traffic delays. The return leg will not encounter the same level of congestion, so this return trip is faster. Thus the round-trip time for a block 1 (long evacuation) wave is estimated at 24 hours.

Similarly a block 2 (short evacuation) one way trip is estimated at 2 hours without traffic congestion, so a range of 5 to 9.5 hours is the estimated time in an evacuation scenario. The return trip is also faster thus the round trip for the short evacuation wave is estimated at 12 hours. This time includes mustering personnel, loading the vehicles, traveling to the evacuation site, unloading at the site and returning. Refueling time is also included.

b. ENCMCFI Transportation Assets

For those personnel who must be moved by the government, a limited number of evacuation means are available. Table 5 lists the organic ENCMCFI evacuation assets. The total number of personnel that can be moved in one wave with these assets is 3,945. This is well short of the necessary total positive move population of

approximately 11,300; thus, these assets will be used in successive round trips to enable the complete evacuation. Both short and long moves are included in the 11,300 personnel estimate. The assets must complete two round trips and a one-way trip to move the entire population. The troop rotation cycle may increase the total to 18,000. Five waves would evacuate the entire positive move population in this case.

Asset Name:	Asset Type:	Number Available	Capacity	Total per Wave
Inter-City Bus	1	2	49	98
Adult Bus	2	18	44	792
School Bus	3	17	44	748
46 PAX Troop Transport	4	4	46	184
56 PAX Troop Transport	5	1	56	56
62 PAX Troop Transport	6	1	62	62
20 PAX Adult Bus	7	1	20	20
28 PAX Adult Bus	8	8	28	224
36 PAX Adult Bus	9	3	36	108
12 PAX Van	10	13	12	156
8 PAX Van	11	139	8	1112
7 PAX Compact Van	12	11	7	77
Cargo Van	13	154	2	308
			Total:	3945

Table 5. Available transportation assets at ENCMCFI from Marine Corps Installations East

There are other options for the movement of these personnel, such as contracted commercial buses; however, buses require at least 24 hours of prior notice before they are available. These buses will be in high demand in the face of an approaching storm. In the aftermath of Hurricane Katrina, was been determined that in future similar emergencies, these assets will be managed by the Federal Emergency Management Agency (FEMA). These buses will be tasked at the national level to assist in the evacuation of the entire population. Any use of these buses is uncertain and for this reason, in this thesis, these assets are not included in the evacuation asset matrix.

Activating self-evacuation is the last decision that can be made as a storm approaches because of the flexibility of people leaving in their own vehicles. If this population is ordered to depart simultaneously, the local transportation infrastructure will not support the traffic. The evacuation would be occurring in the midst of evacuating other local municipalities and counties. Traffic flow rates will be greatly reduced. This

execution must be phased over time. The interaction with other evacuation efforts will determine clearance times from the coast of North Carolina. Up to 24 hours would be needed for self-evacuation.

3. Evacuation Costs

a. Travel Costs

When the Marine Corps orders an evacuation, the costs incurred by those evacuating become the responsibility of the government. This not only extends to the population that the government has to positively move, but to those who self-evacuate as well (U.S. Marine Corps Forces Command, 2007). This travel cost is not insignificant, so cost-saving measures are in the best interest of the Marine Corps. Costs for government-owned transportation assets are calculated based on ENCMCFI planning estimates (E. Dewald, Deputy Director for Plans and Operations, ENEMCFI, personal communication, Dec 3, 2006). Individual travel costs are computed by using an estimate of self evacuation distances and current government privately-owned-vehicle mileage reimbursement rates from the JFTR. Travel costs are a function of the vehicle making the trip, and not the number of personnel moved.

b. Temporary Additional Duty Costs

All personnel ordered to evacuate will be entitled to lodging expenses and per-diem rates for meals. This increases evacuation costs considerably because of the possibility of a long-duration evacuation in a catastrophic storm. Let $C_L(b)$ be the TAD cost for one person from block *b* for one day as referenced from the JFTR.

c. Deaths and Injuries

With approximately 100,000 Marines, family members and civilian personnel (E. Dewald, Deputy Director for Plans and Operations, ENEMCFI, personal communication, Dec 3, 2006), moving large distances in the midst of a large-scale coastal evacuation, traffic fatalities and injuries are likely. Assuming an average one-way

evacuation distance of 250 miles, the evacuation will consist of over 50,000,000 passenger miles in a congested road network. According to the National Transportation Safety Administration, in 2004, the average rate of fatalities on the roads of the United States was 1.44 per 100,000,000 passenger miles with 94 injuries over the same distance (U.S. Department of Transportation, 2005). These figures were compiled over the entire year and not exclusively during times of crisis and extreme congestion. These estimates may not reflect the actual numbers of traffic fatalities and injuries.

C. THE OVERALL DECISION PROBLEM

Given all of the factors, deciding whether to order a base-wide evacuation is extremely complex and involves making very large financial commitments based on the occurrence of events whose probabilities are not well known. The decision is essentially a balancing of financial estimates with projected injuries and fatalities. When a forecast is issued at time τ , the decision is whether to use the available assets to evacuate a wave of personnel. This is not a one-time decision. A new forecast is issued every six hours. As the storm forecast changes, a decision not to continue evacuation may result.

1. Calculation of Individual Components

Two separate decision processes exist. One involves personnel who require provided transportation (positive move population). The other involves the much larger population who will self evacuate. The reason for this separation is based on transportation needs. The positive move population requires more logistical support, and requires a longer evacuation lead time than the self-evacuation population. Both compete for organic transportation assets. A wave of 3,945 long evacuation personnel are assumed to be evacuated first (24 hours round-trip) the second wave consists of the 3,945 short evacuation personnel are evacuated (12 hours round trip). Next 3,710 long evacuation personnel (12 hours one way) and 210 short evacuation personnel (6 hours one way) comprise the third wave. This ordering reflects the constraints of these personnel based on their military duties. A complete positive move evacuation will require approximately 24+12+12 = 48 hours. When the last wave of vehicles reaches

their evacuation destination, those vehicles will remain at that location; thus, the last wave is only calculated to be a one way trip.

Let $A(v,\tau,b)$ be the number of transportation assets of type *v* used at time τ to evacuate personnel from block *b*. To determine the assets available at a given time, the number of assets sent on earlier evacuation trips (not yet available) must be calculated. This calculation is displayed in equation 3.1. $A'(v,\tau)$ is the number of vehicles of type v available for evacuation at time τ and acts as a constraint on $A(v,\tau,b)$ as is indicated in equation 3.2

$$A'(v,\tau)=\left[A_0(v)-\sum_{\substack{t\in T_F\\ t>\tau-24}}A(v,t,1)-\sum_{\substack{t\in T_F\\ t>\tau-12}}A(v,t,2)\right]\ \forall v,\tau \tag{3.1}$$

Where $A_0(v)$ is the initial number of vehicle of type *v* at ENCMCFI

$$\left[A(v,\tau,1)+A(v,\tau,2)\right]\leq A'(v,\tau)\ \forall v,\tau \tag{3.2}$$

To determine risk levels, it is important to calculate the number of personnel evacuated at each forecast decision point. Let $v=$ transportation asset type, $v\in\{1,2,...14\}$, and let $Q(v)$ be the capacity of transportation asset *v*. Let $H(b,t)$ be the number of personnel in each block *b* that are evacuated from ENCMCFI at time *t*, $H(b,t)=\sum_{v}A(v,t,b)\times Q(v)\ \forall b,t$ The maximum number of personnel that can be evacuated from ENCMCFI at time τ is displayed by equation 3.3.

$$\sum_{v}A'(v,\tau)\times Q(v) \tag{3.3}$$

a. Direct Evacuation Cost Calculation

The evacuation decision is assumed to be an all-or-nothing proposition; if it makes sense to evacuate one person, than it will make sense to evacuate the maximum number possible at that time step. At each decision time the first cost that must be calculated is the cost of the evacuation using all available evacuation assets. This cost is

displayed in equation 3.4. Let $C_E(\tau,\tau+s)$ be the cost of evacuating (transportation plus TAD costs) for those people evacuated at time $\tau+s$ incurred by the decision to evacuate made at time τ. Let $C_T(b,v)$ be the cost of asset *v* executing a block *b* evacuation wave and let $C_L(b)$ be the TAD cost for one person from block *b* for one day as referenced from the JFTR. For the purpose of this thesis, the evacuation duration is assumed to be seven days, under the assumptions that most evacuations will occur approximately two days prior to the arrival of the storm and it will take five days to return personnel to the area.

$$C_E(\tau,\tau+s) = \underbrace{\sum_v \sum_b C_T(b,v) \times A(v,\tau+s,b)}_{\text{Direct Evac Costs}} + \sum_b \left(\underbrace{C_L(b) \times \overbrace{(7)}^{\substack{\text{duration of}\\ \text{evacuation (days)}}} \times H(b,\tau+s)}_{\text{TAD costs}} \right) \tag{3.4}$$

b. Evacuation Risk Cost Calculation

The evacuation risk at a particular decision time must be estimated. Using the data outlined in this chapter, this estimate is displayed in equation 3.5. Let $C_{RE}(\tau,\tau+s)$ be expected transportation risk cost of injuries and fatalities in the population evacuated at time $\tau+s$ (monetized penalty incurred by the evacuation decision made at time τ). Let C_T^i be the risk cost (≥\$257,000) for each injury experienced during the course of an evacuation. Let $Z_T^i(b)$ be the probability a person from block *b* will experience an injury in the course of an evacuation (94 per 100,000,000 passenger miles). Let C_T^f be the risk cost (≥\$625,000) for each fatality experienced in the course of an evacuation. Let $Z_T^f(b)$ be the probability per person from block *b* of fatality experienced in the course of an evacuation (1.44 per 100,000,000 passenger miles).

$$C_{RE}\left(\tau,\tau+s\right)=\sum_{b}H(b,\tau+s)\times\left(\left(Z_T^i(b)\times C_T^i\right)+\left(Z_T^f(b)\times C_T^f\right)\right) \quad (3.5)$$

c. Evacuation Fatality Risk Calculation

Similarly, the expected number of fatalities can be estimated. Let $L_{RE}\left(\tau,\tau+s\right)$ be the expected number of fatalities in the population evacuated at time $\tau+s$ due to risk incurred by the evacuation decision made at time τ.

$$L_{RE}\left(\tau,\tau+s\right)=\sum_{b}H(b,\tau+s)\times Z_T^f(b) \quad (3.6)$$

d. Storm Risk Cost Calculation

Risk to personnel who are not evacuated is calculated as described in Chapter II. The estimate is displayed in equation 3.7. Let $C_{RS}\left(\tau,R_M(\tau,\tau+s)\right)$ be the storm-related risk measured by expected fatality and injury costs (monetized penalty) if no further evacuations occur after $\tau+s$ when the decision to evacuate is made at time τ. Recall that $R_M(\tau,\tau+s)$ is the number of personnel remaining at ENCMCFI if no further evacuations occur after time $\tau+s$ and the evacuation starts at time τ. Let C_S^i be the penalty cost for each injury due to direct storm effects (≥\$257,000). Let Z_S^i be the probability of injury per person due to direct storm effects. Let C_S^f be the penalty cost per fatality due to direct storm effects (≥\$625,000). Let Z_S^f be the probability of fatality per person due to direct storm effects. Let C_B be the cost of supporting one person at ENCMCFI during post-storm cleanup operations.

$$C_{RS}\left(\tau,R_M(\tau,\tau)\right)=\left(\left(Z_S^i\times C_S^i\right)+\left(Z_S^f\times C_S^f\right)+C_B\right)\times R_M(\tau,\tau) \quad (3.7)$$

e. Storm Fatality Risk Calculation

The expected number of fatalities due to storm effects for personnel not evacuated must be estimated. Let $L_{RS}\left(\tau,R_M(\tau,\tau)\right)$ be the estimate of storm-related

fatalities incurred if no further evacuations occur after τ. Equation 3.8 displays this calculation.

$$L_{RS}\left(\tau, R_M(\tau,\tau)\right) = Z_S^f \times R_M(\tau,\tau) \tag{3.8}$$

2. Implementation of the Decision model

The decision process becomes a comparison at each decision opportunity of the risk and cost of evacuating at the current decision time versus postponing evacuation until the next forecast is issued in 6 hours versus the risk of not evacuating at all. The major variables in this decision are whether the storm is going to affect ENCMCFI, and whether tropical-storm force winds will interrupt evacuation. The key comparison is between total cost and risk for a full evacuation started at this decision time against the same cost and risk if no action is taken immediately but evacuation is initiated in 6 hours.

a. Cost to Commence Evacuation at Current Time

The expected total evacuation cost for evacuation starting at time τ is displayed in equation 3.9. The expected total evacuation cost includes the cost of evacuating first wave and the cost of evacuating the second and third waves times the probability that tropical storm force winds do not prevent their departures. It is assumed that the first wave will successfully complete evacuations before tropical-storm force winds arrive. Evacuation risk costs in subsequent waves occur because of the probability of tropical storm force winds not interrupting evacuation.

Expected total evacuation costs if initiated at time τ

$$= \underbrace{\underbrace{C_E(\tau,\tau)}_{\text{Direct Evacuation Expected Cost}} + \underbrace{C_{RE}(\tau,\tau)}_{\text{Evacuation Expected Risk Costs}}}_{\text{Wave 1 Expected Evacuation Costs}}$$

$$+ \underbrace{\underbrace{\left[\prod_{\substack{t \in T_s \\ 12 \le t \le 24}} \left(1 - \left(\rho_{34}(\tau, \tau + t)\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34} \\ \text{Kts within the next 24 hours}}} \times \left[\underbrace{C_E(\tau, \tau + 24)}_{\substack{\text{Direct Evacuation Expected} \\ \text{Cost of Wave 2}}} + \underbrace{C_{RE}(\tau, \tau + 24)}_{\substack{\text{Evacuation Risk Expected} \\ \text{Cost of Wave 2}}}\right]}_{\text{Wave 2 Expected Evacuation Costs}} \tag{3.9}$$

$$+ \underbrace{\underbrace{\left[\prod_{\substack{t \in T_s \\ 12 \le t \le 36}} \left(1 - \left(\rho_{34}(\tau, \tau + t)\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34} \\ \text{Kts within the next 36 hours}}} \times \left[\underbrace{C_E(\tau, \tau + 36)}_{\substack{\text{Direct Evacuation Expected} \\ \text{Cost of Wave 3}}} + \underbrace{C_{RE}(\tau, \tau + 36)}_{\substack{\text{Evacuation Risk Expected} \\ \text{Cost of Wave 3}}}\right]}_{\text{Wave 3 Expected Evacuation Costs}}$$

Storm costs are the expected costs resulting from the effects of 105 kts winds at ENCMCFI if an evacuation is interrupted by 34 kts winds. For the calculation of this risk, the estimated probability of 34 kts winds occurring prior to a given wave’s evacuation is calculated and multiplied by the estimated probability that 105 kts winds occur after the given wave’s scheduled evacuation. If 34 kts winds should prevent a wave from evacuating, then those personnel will be susceptible to the risk of 105 kts winds. If 105 kts winds occur prior to their evacuation, then 34 kts winds occurred prior to that and thus they would not have been able to evacuate.

Equation 3.10 displays the expected storm costs of an incomplete evacuation of waves two and three: the evacuation is interrupted by tropical storm force winds. The probability that the second and third wave personnel are unable to evacuate is multiplied by the probability that the storm arrives and winds in excess of 105 kts are experienced at ENCMCFI after those evacuation times.

Expected monetized storm risk costs if evacuation is initiated at time τ

$$=\left[\underbrace{\underbrace{\left[1-\left[\prod_{\substack{t\in T_s\\12\le t\le 24}}\left(1-\left(\rho_{34}(\tau,\tau+t)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 34 Kts}\\\text{within the next 24 hours}}}\times\underbrace{\left[1-\left[\prod_{\substack{t\in T_s\\27\le t\le 120}}\left(1-\left(\rho_{105}(\tau,\tau+t)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 105 Kts after 27 hours}\\\text{but before 120 hours}}}}_{\text{Probability that Wave 2 is unable to evacuate and 105+ winds Impact ENCMCFI}}\times\underbrace{C_{RS}\left(\tau+24,R_M(\tau,\tau+24)\right)}_{\text{Storm Risk Cost for Wave 2}}\right]$$

$$+\left[\underbrace{\underbrace{\left[1-\left[\prod_{\substack{t\in T_s\\12\le t\le 36}}\left(1-\left(\rho_{34}(\tau,\tau+t)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 34 Kts}\\\text{within the next 36 hours}}}\times\underbrace{\left[1-\left[\prod_{\substack{t\in T_s\\39\le t\le 120}}\left(1-\left(\rho_{105}(\tau,\tau+t)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 105 Kts after 39 hours}\\\text{but before 120 hours}}}}_{\text{Probability that Wave 3 is unable to evacuate and 105+ winds Impact ENCMCFI}}\times\underbrace{C_{RS}\left(\tau+36,R_M(\tau,\tau+36)\right)}_{\text{Storm Risk Cost for Wave 3}}\right] \quad (3.10)$$

Therefore the expected cost of evacuating, or continuing evacuation at the current forecast time is: $\left[(3.9)+(3.10)\right]$.

b. Expected Fatalities at Current Forecast Time

The expected number of fatalities due to evacuation is calculated in the same manner as the cost risk equations 3.9 and 3.10. Equation 3.11 displays the expected total number of evacuation fatalities due to an evacuation starting at time τ.

Expected number of fatalities due to evacuation at time τ

$$=\underbrace{L_{RE}(\tau,\tau)}_{\substack{\text{Expected}\\\text{Wave 1 Evacuation Fatalities}}}+\underbrace{\underbrace{\left[\prod_{\substack{t\in T_s\\12\le t\le 24}}\left(1-\left(\rho_{34}(\tau,\tau+t)\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34}\\\text{Kts within the next 24 hours}}}\times\left[\underbrace{L_{RE}(\tau,\tau+24)}_{\substack{\text{Estimated Wave 2 Evacuation}\\\text{Fatality Risk}}}\right]}_{\text{Expected Wave 2 Evacuation Fatalities}}$$

$$+\underbrace{\underbrace{\left[\prod_{\substack{t\in T_s\\12\le t\le 36}}\left(1-\left(\rho_{34}(\tau,\tau+t)\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34}\\\text{Kts within the next 36 hours}}}\times\left[\underbrace{L_{RE}(\tau,\tau+36)}_{\substack{\text{Estimated Wave 3 Evacuation}\\\text{Fatality Risk}}}\right]}_{\text{Expected Wave 3 Evacuation Fatalities}} \quad (3.11)$$

Similarly, equation 3.12 displays the expected number of fatalities from storm risk.

Expected number of fatalities due to storm effects at time τ

$$= \left[\underbrace{\underbrace{\left[1-\left[\prod_{\substack{t\in T_s \\ 12\le t\le 24}}\left(1-\left(\rho_{34}\left(\tau,\tau+t\right)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 34 Kts} \\ \text{within the next 24 hours}}} \times \underbrace{\left[1-\left[\prod_{\substack{t\in T_s \\ 27\le t\le 120}}\left(1-\left(\rho_{105}\left(\tau,\tau+t\right)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 105 Kts after 27 hours} \\ \text{but before 120 hours}}}}_{\text{Probability that Wave 2 is unable to evacuate and 105+ winds Impact ENCMCFI}} \times \underbrace{L_{RS}\left(\tau+24, R_M\left(\tau,\tau+24\right)\right)}_{\text{Storm Risk Expected Fatalities for Wave 2}} \right]$$

$$+ \left[\underbrace{\underbrace{\left[1-\left[\prod_{\substack{t\in T_s \\ 12\le t\le 24}}\left(1-\left(\rho_{34}\left(\tau,\tau+t\right)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 34 Kts} \\ \text{within the next 24 hours}}} \times \underbrace{\left[1-\left[\prod_{\substack{t\in T_s \\ 27\le t\le 120}}\left(1-\left(\rho_{105}\left(\tau,\tau+t\right)\right)\right)\right]\right]}_{\substack{\text{Probability of Winds exceeding 105 Kts after 27 hours} \\ \text{but before 120 hours}}}}_{\text{Probability that Wave 3 is unable to evacuate and 105+ winds Impact ENCMCFI}} \times \underbrace{L_{RS}\left(\tau+36, R_M\left(\tau,\tau+36\right)\right)}_{\text{Storm Risk Expected Fatalities for Wave 3}} \right] \quad (3.12)$$

c. Cost to Evacuate at Next Forecast Time

To evaluate the expected cost of waiting until the next forecast to start evacuation, the calculations are conducted in much the same manner. Now the probability that the first wave is unable to evacuate due to the arrival of tropical storm force winds enters the equation. This will require new notation since these calculations will be computed concurrently with the ones evaluating the costs of evacuating at the current forecast time. Let $R_M^d(t+6,\tau+6+s)$ be the total number of personnel that remain ENCMCFI at time $\tau+6+s$ if no further evacuations occur after time $\tau+6+s$ due to the evacuation decision made at time $\tau+6$. Let $C_E^d\left(\tau+6,\tau+6+s\right)$ be the cost of evacuating (transportation plus TAD costs) for those people evacuated at time $\tau+6+s$ incurred by the decision to evacuate made at time $\tau+6$. Let $C_{RE}^d\left(\tau+6,\tau+6+s\right)$ be expected transportation cost of injuries and fatalities in the population of people evacuated at time $\tau+6+s$ in monetized penalty incurred by the evacuation decision made at time $\tau+6$. The expected evacuation costs are displayed in equation 3.14. The expected direct evacuation cost includes the cost of evacuating all the positive move population multiplied by the probability that tropical storm force winds have not prevented their departure. The evacuation risk costs are calculated in the same manner.

Note that these expected costs will be less than or equal to the expected evacuation costs in equation 3.4 because they are multiplied by the probability that tropical-storm force winds will arrive and prevent the costly evacuation.

Expected total evacuation costs if initiated at time $\tau + 6$

$$= \underbrace{\underbrace{\left[1-\left(\rho_{34}\left(\tau,\tau+6\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34}\\ \text{Kts within the next 6 hours}}} \times \left[\underbrace{C_E^d\left(\tau+6,\tau+6\right)}_{\substack{\text{Direct Evacuation Cost}\\ \text{for delay of 6 hrs.}}} + \underbrace{C_{RE}^d\left(\tau+6,\tau+6\right)}_{\substack{\text{Evacuation Risk Costs}\\ \text{for delay of 6 hrs.}}}\right]}_{\text{Wave 1 Expected Evacuation Costs}}$$

$$+ \underbrace{\underbrace{\left[\prod_{\substack{t\in T_s\\ 12\le t\le 30}} \left(1-\left(\rho_{34}\left(\tau,\tau+t\right)\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34}\\ \text{Kts within the next 30 hours}}} \times \left[\underbrace{C_E^d\left(\tau+6,\tau+30\right)}_{\text{Direct Evacuation Cost of Wave 2}} + \underbrace{C_{RE}^d\left(\tau+6,\tau+36\right)}_{\text{Evacuation Risk Cost of Wave 2}}\right]}_{\text{Wave 2 Expected Evacuation Costs}}$$

$$+ \underbrace{\underbrace{\left[\prod_{\substack{t\in T_s\\ 12\le t\le 42}} \left(1-\left(\rho_{34}\left(\tau,\tau+t\right)\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34}\\ \text{Kts within the next 42 hours}}} \times \left[\underbrace{C_E^d\left(\tau+6,\tau+42\right)}_{\text{Direct Evacuation Cost of Wave 3}} + \underbrace{C_{RE}^d\left(\tau+6,\tau+42\right)}_{\text{Evacuation Risk Cost of Wave 3}}\right]}_{\text{Wave 3 Expected Evacuation Costs}} \qquad (3.14)$$

Expected storm costs are calculated as shown in equation 3.15 by multiplying the probability ENCMCFI personnel are unable to evacuate by the probability of winds in excess of 105 kts at ENCMCFI.

Expected monetized storm risk costs if evacuation is initiated at time $\tau + 6$

$$
= \left[\underbrace{ \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 0 \le t \le 6}} \left(1 - \left(\rho_{34}(\tau, \tau + t)\right)\right) \right] \right]}_{\substack{\text{Probability of Winds exceeding 34 Kts} \\ \text{within the next 6 hours}}} \times \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 9 \le t \le 120}} \left(1 - \left(\rho_{105}(\tau, \tau + t)\right)\right) \right] \right]}_{\substack{\text{Probability of Winds exceeding 105 Kts after 9 hours} \\ \text{but before 120 hours}}} \times \underbrace{C_{RS}^{d}\left(\tau + 6, R_M^d(\tau + 6, \tau + 6)\right)}_{\text{Storm Risk Cost for Wave 1}} }_{\text{Probability that Wave 1 is unable to evacuate and 105+ winds Impact ENCMCFI}} \right]
$$

$$
+ \left[\underbrace{ \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 0 \le t \le 30}} \left(1 - \left(\rho_{34}(\tau, \tau + t)\right)\right) \right] \right]}_{\substack{\text{Probability of Winds exceeding 34 Kts} \\ \text{within the next 30 hours}}} \times \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 33 \le t \le 120}} \left(1 - \left(\rho_{105}(\tau, \tau + t)\right)\right) \right] \right]}_{\substack{\text{Probability of Winds exceeding 105 Kts after 33 hours} \\ \text{but before 120 hours}}} }_{\text{Probability that Wave 2 is unable to evacuate and 105+ winds Impact ENCMCFI}} \times \underbrace{C_{RS}^{d}\left(\tau + 30, R_M^d(\tau + 6, \tau + 30)\right)}_{\text{Storm Risk Cost for Wave 2}} \right]
$$

$$
+ \left[\underbrace{ \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 0 \le t \le 42}} \left(1 - \left(\rho_{34}(\tau, \tau + t)\right)\right) \right] \right]}_{\substack{\text{Probability of Winds exceeding 34 Kts} \\ \text{within the next 42 hours}}} \times \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 45 \le t \le 120}} \left(1 - \left(\rho_{105}(\tau, \tau + t)\right)\right) \right] \right]}_{\substack{\text{Probability of Winds exceeding 105 Kts after 45 hours} \\ \text{but before 120 hours}}} }_{\text{Probability that Wave 3 is unable to evacuate and 105+ winds Impact ENCMCFI}} \times \underbrace{C_{RS}^{d}\left(\tau + 42, R_M^d(\tau + 6, \tau + 42)\right)}_{\text{Storm Risk Cost for Wave 3}} \right] \tag{3.15}
$$

The expected cost of waiting until the next forecast is issued before initiating or continuing evacuation can be calculated by: $\left[(3.14) + (3.15)\right]$

d. Expected Fatalities at Next Forecast Time

The expected number of fatalities due to evacuation transportation for an evacuation that starts at $\tau + 6$ is calculated in the same manner as the risk cost equations 3.14 and 3.15. Let $L_{RE}^{d}\left(\tau + 6, \tau + 6 + s\right)$ be the expected number of fatalities in the population of people evacuated at time $\tau + 6 + s$ due to transportation risk incurred by the evacuation decision made at time $\tau + 6$. Equation 3.16 displays the expected total number of evacuation fatalities due to evacuation starting at time $\tau + 6$.

Expected number of fatalities due to storm effects at time τ

$$= \left[\underbrace{\underbrace{\left[1-\left(\rho_{34}\left(\tau,\tau+6\right)\right)\right]}_{\substack{\text{Probability of Winds NOT exceeding 34} \\ \text{Kts within the next 6 hours}}} \times \underbrace{L^{d}_{RE}\left(\tau+6,\tau+6\right)}_{\substack{\text{Expected Evacuation Fatalities of Wave 1} \\ \text{when evacuation start is delayed 6 hrs,}}}}_{\text{Wave 1 Evacuation Expected Fatalities}} \right]$$

$$+ \underbrace{\underbrace{\left[\prod_{\substack{t\in T_s \\ 12\le t\le 30}} \left(1-\left(\rho_{34}\left(\tau,\tau+t\right)\right)\right) \right]}_{\substack{\text{Probability of Winds NOT exceeding 34} \\ \text{Kts within the next 30 hours}}} \times \left[\underbrace{L^{d}_{RE}\left(\tau+6,\tau+30\right)}_{\substack{\text{Expected Evacuation Fatalities of Wave 2} \\ \text{when evacuation start is delayed 6 hrs.}}} \right]}_{\text{Wave 2 Evacuation Expected Fatalities}}$$

$$+ \underbrace{\underbrace{\left[\prod_{\substack{t\in T_s \\ 12\le t\le 42}} \left(1-\left(\rho_{34}\left(\tau,\tau+t\right)\right)\right) \right]}_{\substack{\text{Probability of Winds NOT exceeding 34} \\ \text{Kts within the next 42 hours}}} \times \left[\underbrace{L^{d}_{RE}\left(\tau+6,\tau+42\right)}_{\substack{\text{Expected Evacuation Fatalities of Wave 3} \\ \text{when evacuation start is delayed 6 hrs.}}} \right]}_{\text{Wave 3 Evacuation Expected Fatalities}} \qquad (3.16)$$

Similarly, equation 3.17 displays the expected number of fatalities from storm risk if the evacuation decision is made at τ +6.

Expected fatalities due to storm risk if evacuation is initiated at time $\tau + 6$

$$
\begin{aligned}
= & \left[\underbrace{\underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 0 \le t \le 6}} \left(1 - \left(\rho_{34}\left(\tau, \tau + t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 34 Kts within the next 6 hours}} \times \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 9 \le t \le 120}} \left(1 - \left(\rho_{105}\left(\tau, \tau + t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 105 Kts after 9 hours but before 120 hours}}}_{\text{Probability that Wave 1 is unable to evacuate and 105+ winds Impact ENCMCFI}} \times \underbrace{L_{RS}\left(\tau + 6, R_M^d(\tau + 6, \tau + 6)\right)}_{\text{Expected Storm Fatalities for Wave 1}} \right] \\
+ & \left[\underbrace{\underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 0 \le t \le 30}} \left(1 - \left(\rho_{34}\left(\tau, \tau + t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 34 Kts within the next 30 hours}} \times \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 33 \le t \le 120}} \left(1 - \left(\rho_{105}\left(\tau, \tau + t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 105 Kts after 33 hours but before 120 hours}}}_{\text{Probability that Wave 2 is unable to evacuate and 105+ winds Impact ENCMCFI}} \times \underbrace{L_{RS}\left(\tau + 30, R_M^d(\tau + 6, \tau + 30)\right)}_{\text{Expected Storm Fatalities for Wave 2}} \right] \\
+ & \left[\underbrace{\underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 0 \le t \le 42}} \left(1 - \left(\rho_{34}\left(\tau, \tau + t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 34 Kts within the next 42 hours}} \times \underbrace{\left[1 - \left[\prod_{\substack{t \in T_s \\ 45 \le t \le 120}} \left(1 - \left(\rho_{105}\left(\tau, \tau + t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 105 Kts after 45 hours but before 120 hours}}}_{\text{Probability that Wave 3 is unable to evacuate and 105+ winds Impact ENCMCFI}} \times \underbrace{L_{RS}\left(\tau + 42, R_M^d(\tau + 6, \tau + 42)\right)}_{\text{Expected Storm Fatalities for Wave 3}} \right]
\end{aligned}
\tag{3.17}
$$

e. Cost of Not Conducting Evacuation Operations

To determine the expected cost not evacuating, the storm risk cost is calculated as the entire population of ENCMCFI multiplied by the probability that the storm will cause winds to exceed 105 kts at ENCMCFI at some time in the future. Let $R_M^0(t)$ be the total number of personnel that remain ENCMCFI at time *t* if no evacuation operations are conducted. This calculation is displayed in equation 3.18.

Expected monetized storm risk cost if no evacuation of personnel from ENEMCFI takes place

$$= \underbrace{\left[1-\left[\prod_{t\in T_s}\left(1-\left(\rho_{105}\left(\tau,\tau+t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 105 Kts within the next 120 hours}} \times \underbrace{C_{RS}\left(\tau,R_M^0(\tau)\right)}_{\text{Storm Risk Cost for all ENCMCFI personnel}} \tag{3.18}$$

f. Estimated Fatalities from Not Evacuating

To determine the expected number of fatalities resulting from not evacuating, the estimated storm fatalities must be calculated for the entire population of ENCMCFI multiplied by the probability that the storm will cause winds to exceed 105 kts at ENCMCFI at some time in the future. This calculation is displayed in equation 3.19.

Estimated fatalities due to storm effects if no evacuation takes place

$$= \underbrace{\left[1-\left[\prod_{t\in T_s}\left(1-\left(\rho_{105}\left(\tau,\tau+t\right)\right)\right)\right]\right]}_{\text{Probability of Winds exceeding 105 Kts within the next 120 hours}} \times \underbrace{L_{RS}\left(\tau,R_M^0(\tau)\right)}_{\text{Estimated Expected Number of Storm Fatalities if all ENCMCFI Personnel remain at base}} \tag{3.19}$$

3. Decision Rule

Quantitative support to a base commander's evacuation decision is provided by this model output in terms of deterministic output based on two decision rules. Two sets of decision rules are developed: the first computes expected costs and the second computes expected fatalities. Both decision rules use two comparisons. For the expected costs decision rule, the first comparison is whether the expected cost of evacuating at the current time $\left[(3.9)+(3.10)\right]$, is less than the expected cost resulting from not evacuating (3.18). If the expected cost of evacuating is less, an evacuation is considered. This comparison will prevent evacuation operations from being considered when the probability of having a major impact at ENCMCFI is small.

Similarly an analogous calculation of expected fatalities if an evacuation starts at the current forecast point is compared to the expected number fatalities for no evacuation.

To calculate expected fatalities at this decision time, the first comparison determines whether the expected number of fatalities resulting from evacuating at the current time $\left[(3.11)+(3.12)\right]$, is less than the expected fatalities resulting from not evacuating (3.19).

The second comparison is whether the expected cost to begin evacuation operations now is less than the expected cost of beginning the evacuation at the next forecast decision point $\left[(3.14)+(3.15)\right]$. Costs and (risk-reduction) benefits of removing the population from the ENCMCFI area immediately are compared with costs and benefits of waiting until the next decision point. The risk of waiting six hours for new forecast information is that the probability of being unable to evacuate may increase. The analogous decision rule dealing with expected fatalities is whether the expected number of fatalities from the decision to begin evacuation operations now is less than the expected number of fatalities from beginning the evacuation at the next forecast decision point $\left[(3.16)+(3.17)\right]$. This comparison is conducted by comparing the results of the sum of equations 3.9 and 3.11 with the sum of equations 3.14 and 3.15 for the expected costs. For the expected fatalities, $\left[(3.12)+(3.13)\right]$ and $\left[(3.16)+(3.17)\right]$ are compared.

This estimated cost decision rule is to initiate or continue evacuation only if:

$$\left[(3.9)+(3.10)\right] << \min\left[\left((3.14)+(3.15)\right),(3.18)\right]. \tag{3.20}$$

The estimated fatalities decision rule is:

$$\left[(3.12)+(3.13)\right] << \min\left[\left((3.16)+(3.17)\right),(3.19)\right]. \tag{3.21}$$

If these criteria are met, then evacuation is indicated and will be referred to as the "evacuation signal." Base commanders at ENCMCFI will typically set their own decision thresholds, and will consider both decision rules in their evacuation decision. This model will be further illustrated through the analysis of historical storms in Chapter IV.

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IV. MODEL IMPLEMENTATION AND ANALYSIS

A. INTRODUCTION

In order to study the implications of the model and decision rules outlined in Chapter III, historical storms can be used to identify times when ENCMCFI should have considered evacuation. This chapter applies the model and decision rules to historical storms. Because in recent history no storms have brought 105 kts winds to ENCMCFI, two historical hurricanes ─ Floyd and Isabel ─ will be modified to simulate making landfall with winds in excess of 105 kts. A third, hypothetical, storm has been created to represent the worst case storm for the model. This hypothetical storm is a 165 kts hurricane that makes a slow landfall at ENCMCFI. This storm will be analyzed to determine the conditions that the worst case will produce, in terms of probabilities of 105 kts winds, and the evacuation decision rule.

At ENCMCFI, wind effects are the most dangerous aspect of a hurricane strike; however most hurricane deaths are caused by flooding. Therefore, the threats to life are not as severe for ENCMCFI as for installations in a storm-surge susceptible area. To illustrate how the increased risk associated with storm surge would change the results, analysis in this chapter modifies fatality rates to demonstrate the behavior of the model in areas with storm surge risk. Finally, a sensitivity analysis with respect to the cost of fatalities is conducted.

B. ANALYSIS OF HISTORICAL HURRICANES

Using the decision rules outlined in Chapter III, evacuation decisions based on historical storms are assessed. Hurricane Floyd and Hurricane Isabel are analyzed to assess model output based on known storm end states. Both of these storms were very intense early in their lives, prior to decreasing in intensity before landfall. To model a storm that is a greater threat to ENCMCFI, the intensities of these storms are adjusted

upward. At their strongest points Hurricane Floyd was a strong Category-4 hurricane with 135 kts winds, and Hurricane Isabel was a Category-5 storm with 140 kts winds (National Weather Service, 2000).

To simulate these storms coming ashore at their maximum intensity, their wind intensity profile from their strongest point was copied to the time when they were approaching and making landfall in the vicinity of ENCMCFI. The enhanced-intensity storms will be referred to as Hurricane Floyd+ and Hurricane Isabel+. Appendix 1 displays the forecast intensities and the simulated forecast intensities for Floyd+ and Isabel+. This analysis provides a good illustration of the model in the face of a very dangerous storm. Forecast conditions that trigger model evacuation signals are highlighted.

1. Model Analysis - Hurricane Floyd+ 1999

Prior to looking at the expected costs and fatalities, the analysis of Hurricane Floyd+ must first begin with the model computed probabilities. Hurricane Floyd will make landfall at advisory number 35. Figure 14 displays the results of equations 2.17 and 2.18 for Hurricane Floyd+ for the computation that the probability of winds exceeding 105 kts occurring at ENCMFI at any time in the next 120 hours, and the probability of 34 kts occurring in the next 42 hours as a function of the advisory number (advisories occur every 6 hours). In the three wave evacuation decision, 42 hours would cover the estimated amount of time for all three waves to clear the area (the last wave will require a further 6 hours to reach its destination after clearing the vulnerable area). In Figure 14 and subsequent figures in this chapter, the NHC forecast advisories are listed sequentially along the x-axis. In Figure 14, even with the enhanced intensity, the probability of 105 kts winds reaches its maximum at advisory 32 with a value of approximately 0.16.

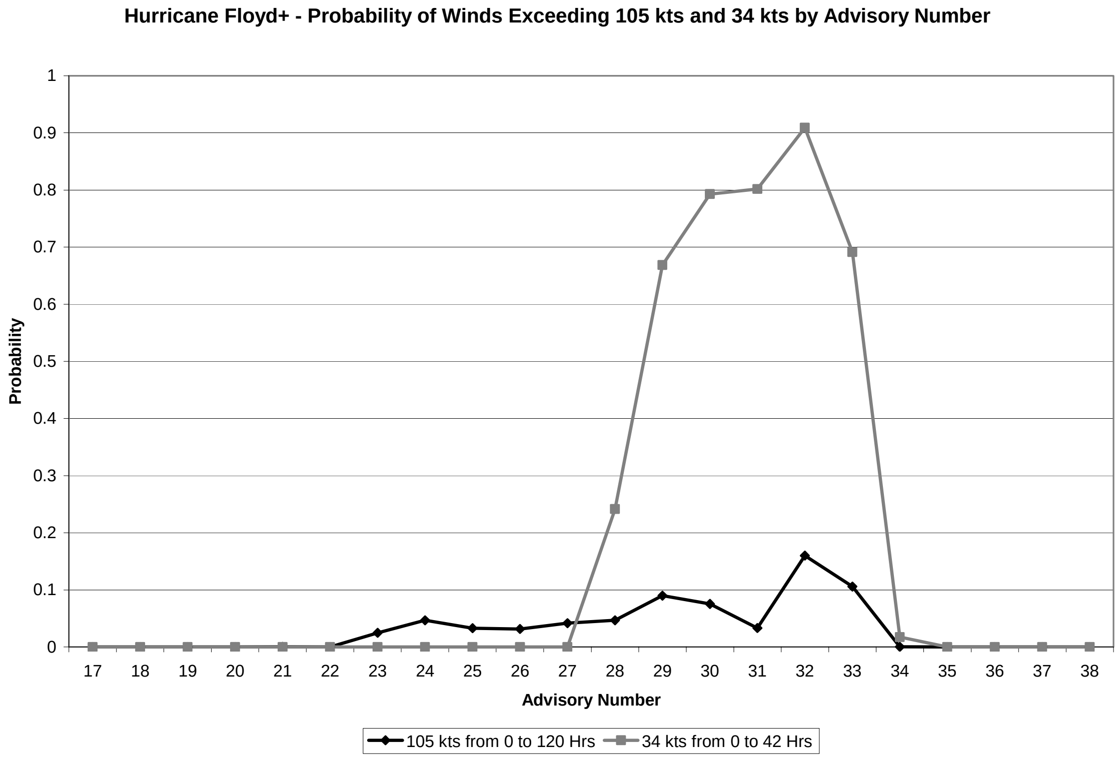

Figure 14. Hurricane Floyd+ Estimated Probabilities of winds in excess of 34 kts and 105 kts at ENCMCFI

Advisory 32 was issued approximately 12 hours prior to landfall. The forecast and actual track of the storm are displayed in Figure 15. In this figure, the outer circle represents the radius of 34 kts winds, which will shortly reach ENCMCFI. The forecast track of the storm is indicated by the larger squares and the actual track is indicated by the small solid squares. Advisory 32 would have been one of the last possible opportunities to evacuate.

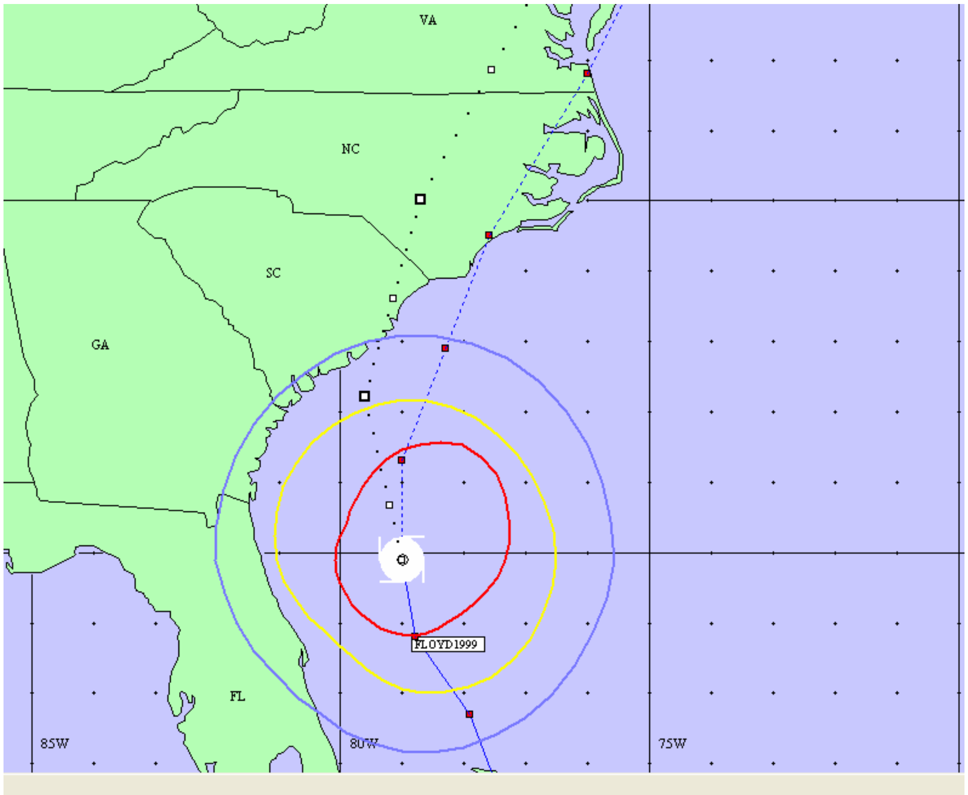

Figure 15. Hurricane Floyd advisory 32 from Hurrevac2000

Figure 16 displays the resulting expected total costs, calculated as described in Chapter III using equations $\left[(3.9)+(3.10)\right]$, $\left[(3.14)+(3.15)\right]$ and (3.18). The expected costs decision rule recommend no evacuation. The first indication of a potential need to evacuate is when the cost of evacuating at a given time is greater than waiting until the next forecast. This cost difference begins at advisory 28. The probability of 34 kts winds in the next 42 hours has just begun to increase (Figure 14). This difference in cost is due to the risk of 34 kts winds interrupting the evacuation. At advisory 28, the cost of waiting until the next forecast is actually lower than the cost of evacuating at advisory 28. The probability of wind in excess of 105 kts is still relatively low at this point while the probability of 34 kts winds is higher. As a result, personnel maybe prevented from evacuating. The 105 kts winds are not forecast to arrive; thus, costs saved by not evacuating are greater than the monetized risk cost of 105 kts winds at ENCMCFI. The decision rule comparing the cost of evacuating now and the cost of not evacuating results in a very clear signal not to evacuate. The cost of never evacuating is

so low that even with the storm 12 hours away at advisory 32, the cost of evacuating is more than twice the cost of never evacuating. Based on the decision rule outlined in Chapter III, evacuation is not indicated in this case.

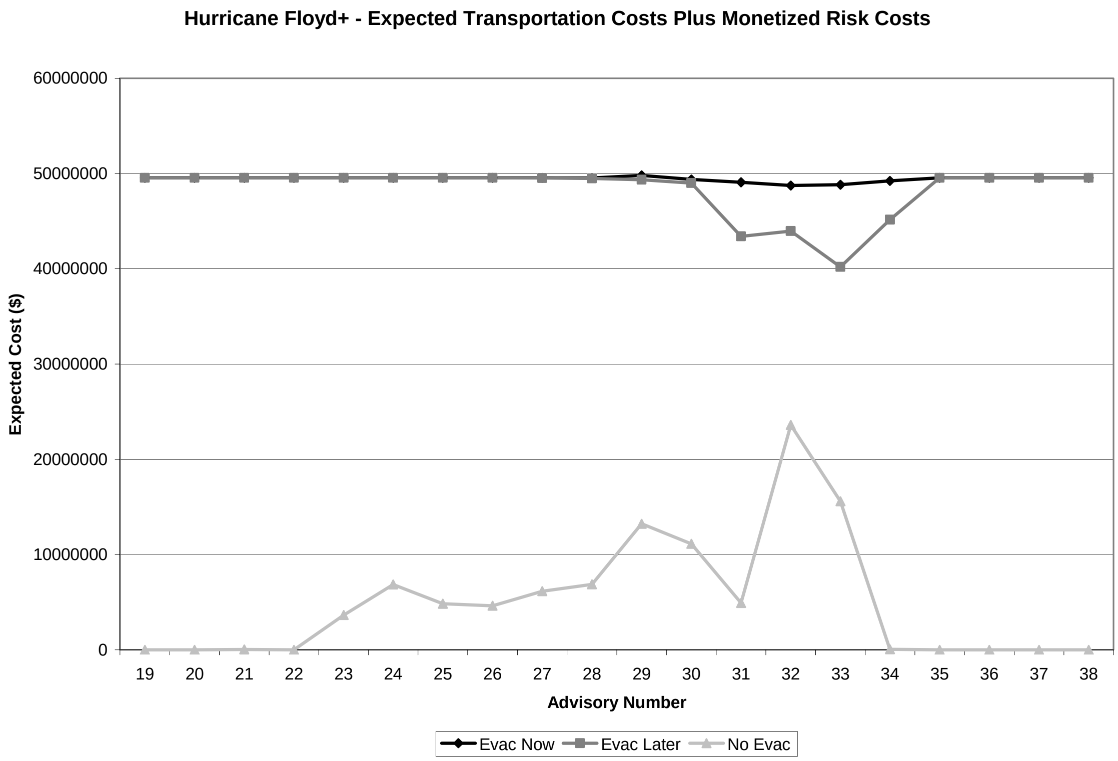

Figure 16. Hurricane Floyd+ expected evacuation cost plus monetized risk cost.

Another way to look at the evacuation decision is to ignore direct evacuation costs and to look only at the expected number of fatalities. Figure 17 displays the expected fatalities from the model using the inputs from Chapter II and Chapter III. Again there is a peak at advisory 32, but the difference in fatality risk between full evacuation and no evacuation at this time step is less than one expected fatality.

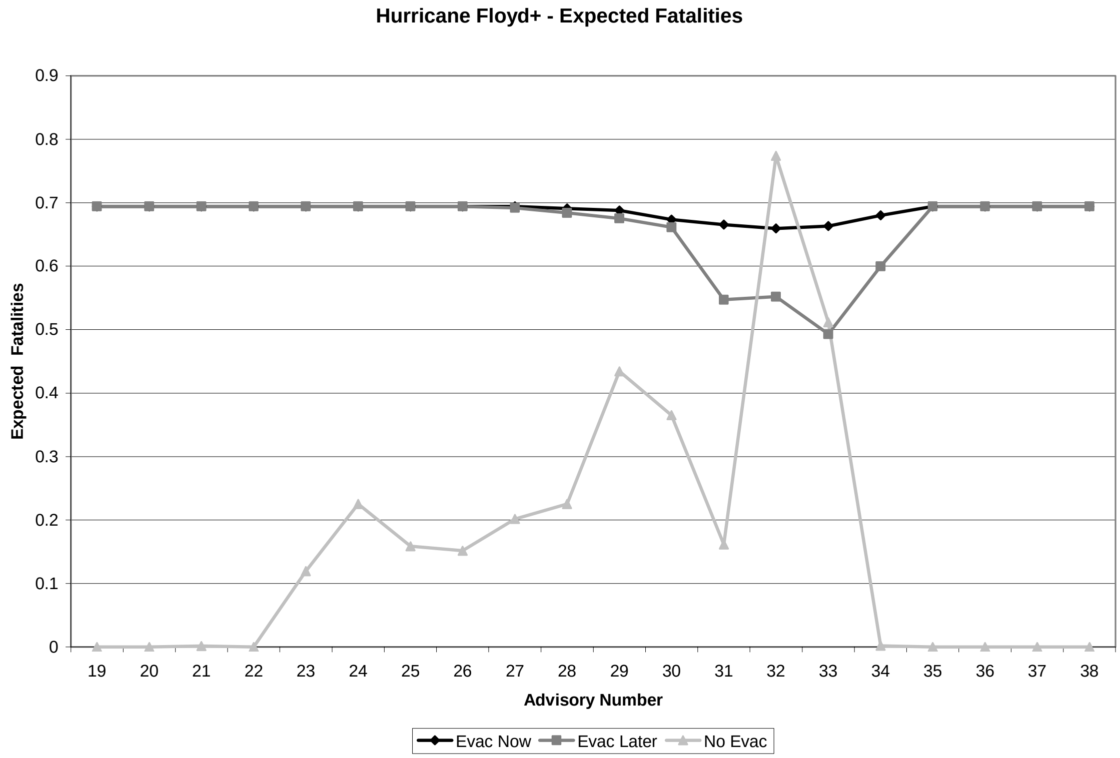

Figure 17. Hurricane Floyd+ Expected Fatalities

Based on these figures, even with the increased intensity of Hurricane Floyd, the model indicates that not evacuating is the best decision. The cost of a full evacuation is approximately \$36M. According to the model the net avoided risk of evacuating is a difference of less than one expected fatality, which cannot justify the \$36M expenditure.

2. Model Analysis - Hurricane Isabel+ 2003

Hurricane Isabel+ yields similar results. Hurricane Isabel makes landfall just north of ENCMCFI at advisory 50. Figure 18 displays the estimated probabilities from the storm model for Hurricane Isabel+. The maximum value of the estimated probability of winds exceeding 105 kts at ENCMCFI is higher than for Floyd+, reaching a maximum of just over 0.2 at forecast advisory 41. This is a significant result because the storm is still approximately 60 hours from landfall, and the probability of 34 kts winds rises sharply after this advisory. Another interesting result is at advisory 47, where there is another increase in the probability of 105 kts winds.

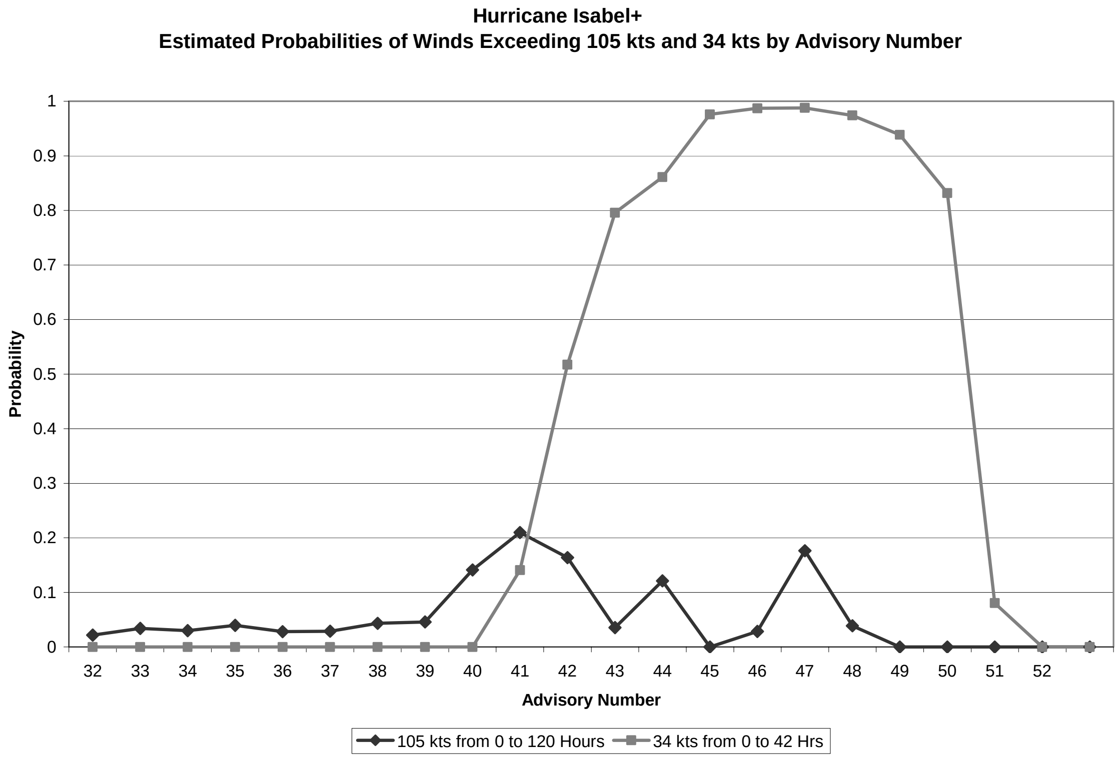

Figure 18. Hurricane Isabel+ Estimated Probabilities of winds in excess of 34 kts and 105 kts at ENCMCFI

At forecast advisory 41 (Figure 19) the forecast (indicated by the large squares) is in line with the actual track of the storm (indicated by the smaller squares), and both are just north of ENCMCFI.

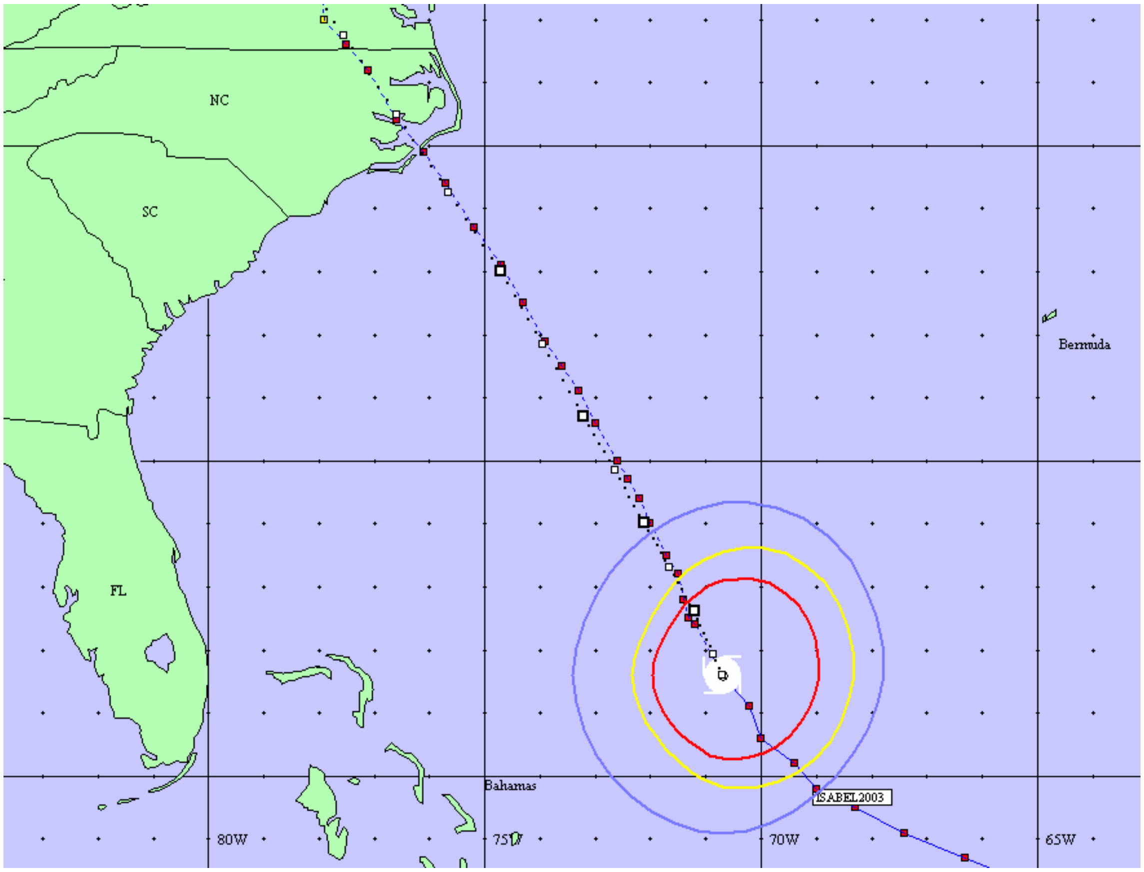

Figure 19. Hurricane Isabel advisory 41 from Hurrevac2000

The results for Isabel+ (Figure 20) are similar to the results from Hurricane Floyd+. The model recommends waiting until the next forecast at all points except advisory 47. There is a definite increase in the cost of not evacuating at advisory 41, but there is no apparent difference between the costs of evacuating now and waiting until the next forecast.

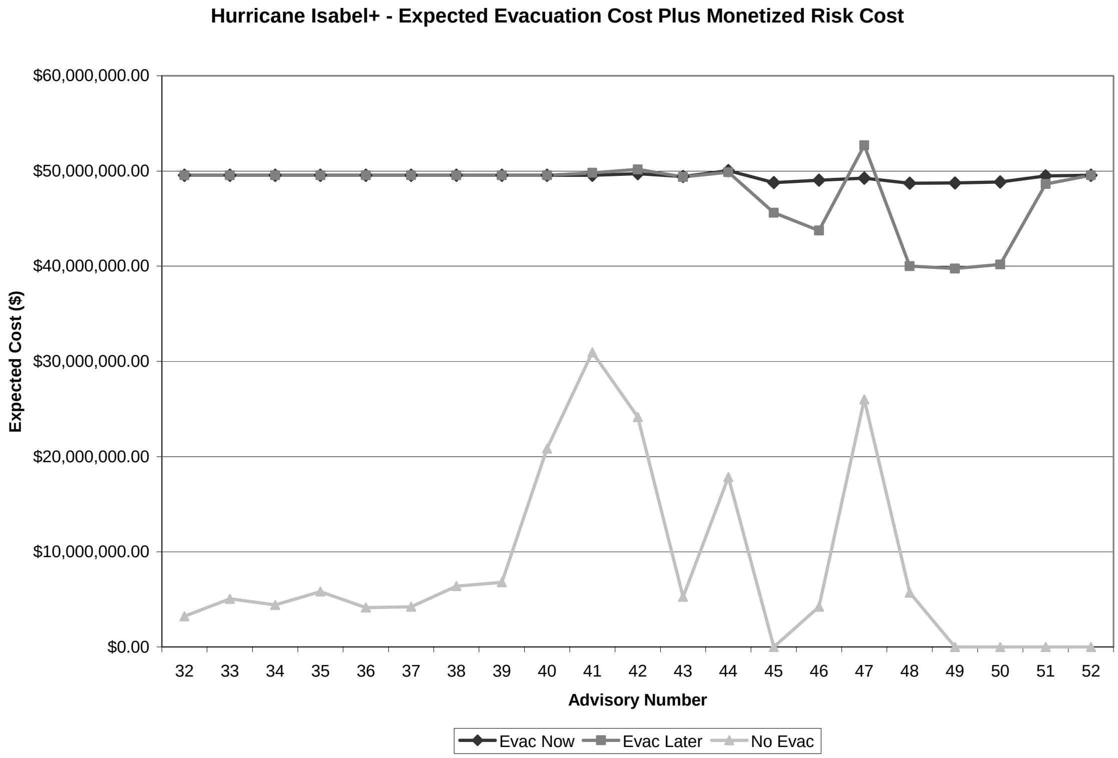

Figure 20. Hurricane Isabel+ expected evacuation cost plus monetized risk cost

If costs were not a factor, and the decision were based purely on an evaluation of the expected fatalities of evacuation or remaining at ENCMCFI, there is still not a clear indication from the model as to which decision is better. Figure 21 shows that when the expected number of fatalities is at its maximum for this storm at advisory 41, the difference between evacuating now and not evacuating at all is less than one expected fatality. There is a slight evacuation signal given at advisory 47, but it is so small that again it cannot justify the expenditure of $36M.

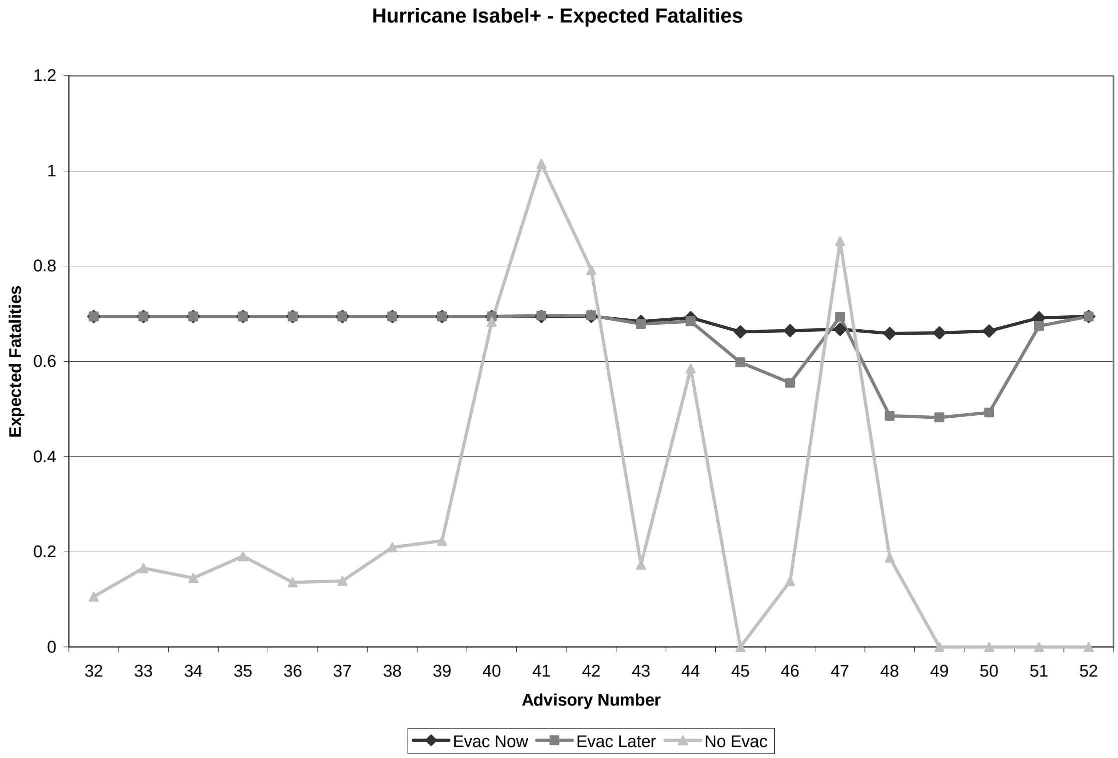

Figure 21. Hurricane Isabel+ Expected Fatalities

Hurricane Floyd and Hurricane Isabel had potential for a major impact on ENCMCFI. Modified hurricanes with greater intensities are considered. Yet the expected cost model does not recommend evacuation for either of the storms even with the modified intensities. The expected number of fatalities for not evacuating is within one expected fatality for both storms. A hypothetical "worst case" storm is created in the next section to study if the model will ever recommend an evacuation.

3. Model Analysis – Worst Case Storm

The worst storm considered for the storm model is a slow moving storm that is very intense. For this test case, a storm that moves in a straight line through ENCMCFI (Figure 22) is created with an intensity of 165 kts for each time step. This figure reflects the highest historical tropical cyclone intensity in the Atlantic basin of 165 kts (Hurricanes Camille 1961, and Allen 1980) (National Weather Service, 2007d). This storm will make landfall at advisory 7. In order to make the evacuation differential as

evident as possible, the storm was created with a very small, 60nm diameter of 34 kts winds, as is indicated by the outer circle in Figure 22.

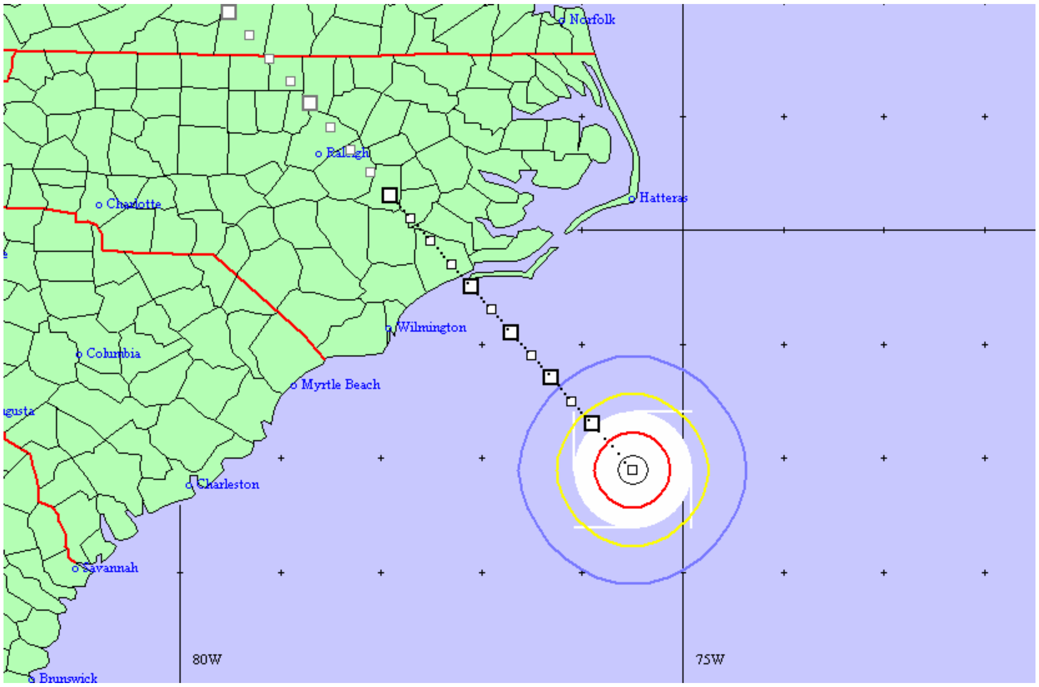

Figure 22. Track and Forecast for Hypothetical "Worst-Case" Storm

The probabilities of winds in excess of 105 kts occurring at ENCMCFI for this storm are much larger than for the two storms analyzed in sections 1 and 2. This is due to the slow movement of the storm and the forecast of the track of the storm directly through the center of ENCMCFI. The position errors are more densely distributed around the forecast point than further away. This density leads to higher probabilities of winds in excess of 105 kts at ENCMCFI in any hurricanes that move through the center of the ENCMCFI box because more of this density is captured by the box in successive forecast time periods. Figure 23 displays the probabilities as the storm makes landfall at advisory 7. The dark line represents the probability of 105 kts winds occurring at ENCMCFI in the next 120 hours, and the gray line represents the probability of 34 kts winds occurring at ENCMCFI in the next 42 hours.

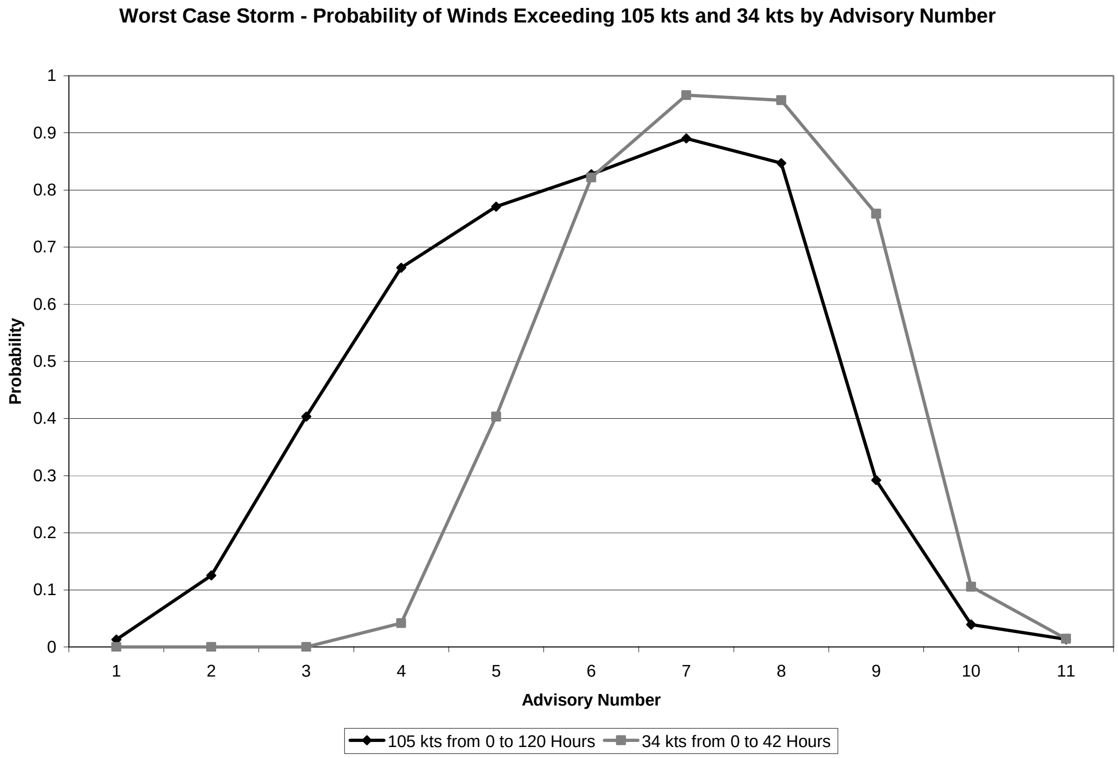

Figure 23. Worst Case Storm Estimated Probabilities of winds in excess of 34 kts and 105 kts at ENCMCFI

With such large probabilities, the evacuation indication should be very clear. The plot of the cost of not evacuating is similar to that of the plot of the estimated probability of 105 kts winds. While there is a clear signal from that test, there is not a difference in the cost of evacuating at the current advisory vs. waiting until the next advisory (until forecast advisory 6) just prior to landfall. This behavior is due to the sensitivity of the evacuation decision to the probability of the arrival of 34 kts winds. In the examples with Hurricanes Floyd+ and Isabel+, the extent of tropical storm force winds was much larger (160 and 200 nm) compared to this hypothetical storm (60nm).

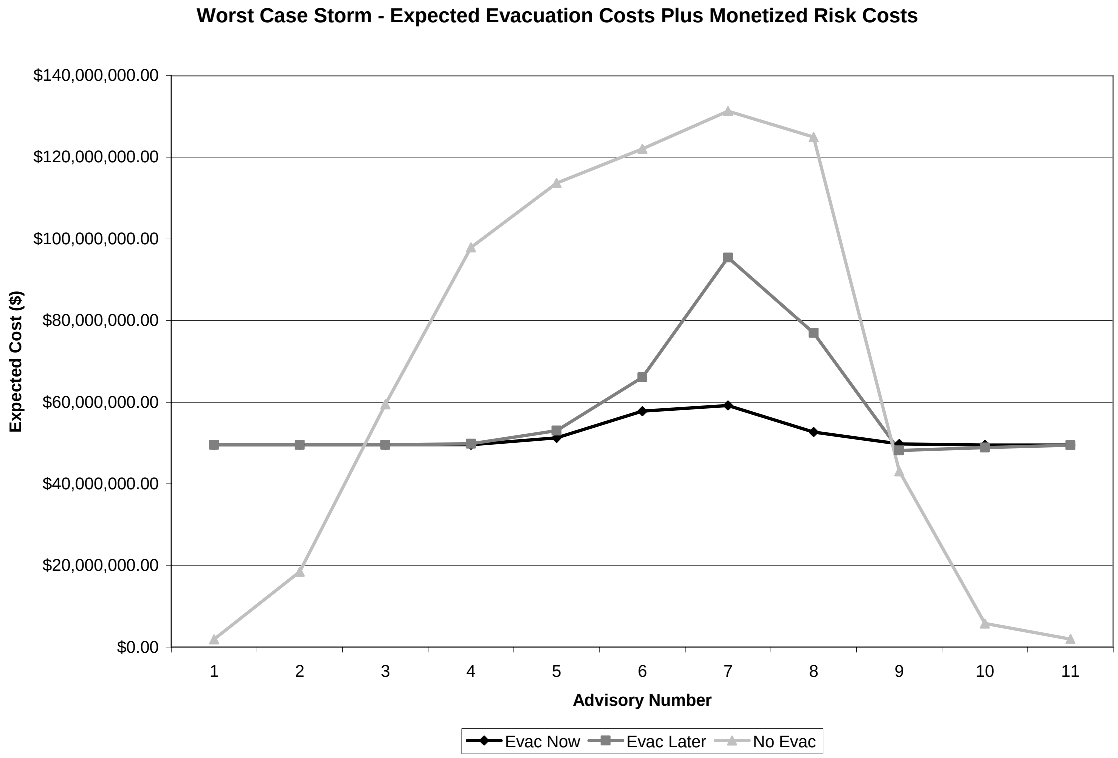

Figure 24. Worst case storm, transportation and monetized risk costs

The fatality output displayed in Figure 25 has a stronger evacuation signal, but the difference in expected fatalities is not large. The reason for the small difference in the expected number of fatalities becomes evident when the rates that are assumed in the evacuation and storm risk fatalities are more closely analyzed. As was discussed in Chapter III, the transportation risk is calculated at 1.44 fatalities per 100,000,000 passenger miles. This translates to approximately 0.8 for the evacuation of all personnel involved. Storm fatalities are estimated to be approximately 5 for the entire population of ENCMCFI, based on data from Table 3.1. Since this worst case storm leads to very large values for the probability of 105 kts winds and 34 kts winds occurring at ENEMCFI, the results of this worst case storm are close to the largest this model can produce using the costs and casualty rates outlined in Chapter III.

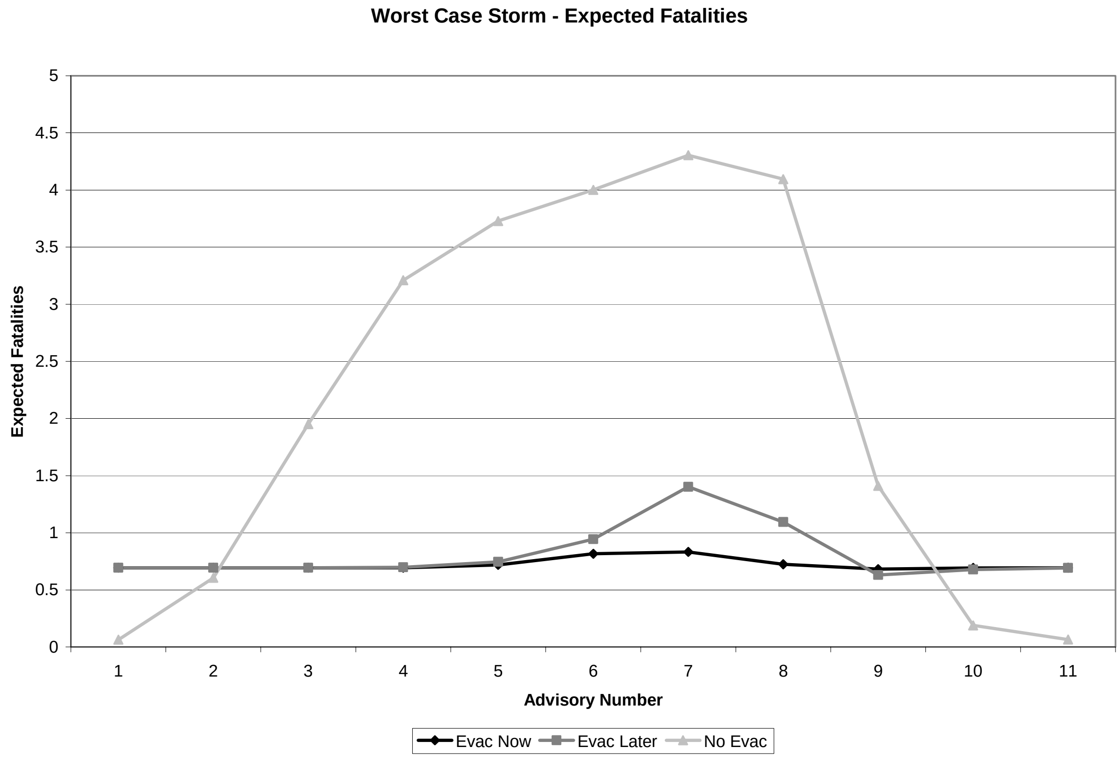

Figure 25. Worst case storm, expected fatalities

Based on this worst case storm, with the rates used for fatalities and casualties used in the model, it is unlikely that there will be a large evacuation signal for ENCMCFI for this storm model with enough lead time to evacuate all ENCMCFI personnel. This is due to the low estimated probabilities of 105 kts winds that occur in enough time to evacuate.

C. ANALYSIS OF THE MODEL INCLUDING STORM SURGE

1. Change of Fatality Rate

According to the analysis results, the current model formulation is unlikely to recommend an evacuation at ENCMCFI under any forecast conditions. The maximum cost of casualties for riding out a worst case storm at ENCMCFI is computed in equation 4.1 using data from Chapter III. The ratio of the evacuation costs (actual and risk costs) and the storm risk cost of the entire ENEMCFI population remaining is 0.337, therefore in order for the model to signal an evacuation, a probability of winds greater than 105 kts

at ENCMCFI of greater than 0.337 is required. Furthermore, a period of at least 48 hours without any probability of 34 kts winds at ENCMCFI is required. Using the information displayed in Figure 23, the probability of 105 kts winds occurring at ENCMCFI does not increase to above 0.337 until advisory 3, which is 24 hours from landfall and only 18 hours from the arrival of 34 kts winds. Even with this worst case hurricane, the model cannot compute an evacuation signal in enough time to complete the evacuation.

$$
\begin{array}{l}
\text{Maximum Storm Risk} \\
\text{Fatality Risk Cost: 4.9 Expected Fatalities} \times \$625{,}000 = \$3{,}062{,}500 \\
\quad \text{Injury Risk Cost: 550 Expected Injuries} \times \$257{,}000 = \$141{,}350{,}000 \\
\qquad\qquad\qquad\qquad\qquad\qquad \text{Total Storm Risk Cost} = \$144{,}412{,}500 \\
\text{Maximum Evacuation Cost:} \\
\text{Fatality Risk Cost: 0.77 Expected Fatalities} \times \$625{,}000 = \$481{,}250 \\
\qquad \text{Injury Risk Cost: 47 Expected Injuries} \times \$257{,}000 = \$12{,}079{,}000 \\
\qquad\qquad\qquad\qquad \text{Transportation and TAD Costs} = \$36{,}200{,}000 \\
\qquad\qquad\qquad\qquad\qquad\qquad \text{Total Evacuation Cost} = \$48{,}760{,}250
\end{array}
\tag{4.1}
$$

This lack of an evacuation signal is a counterintuitive result given the severity of hurricane effects, and is largely due to the minimal storm surge risk that ENCMCFI experiences due to its inland location. Two sets of parameters, aside from the storm probabilities govern the model ─ storm and transportation risk and cost parameters. By changing the values of these parameters, insights into the behavior of the model become apparent. The first change is to remove the assumption that ENCMCFI is in a location that is safe from storm surge. A fatality rate of 0.00237 was experienced along the Mississippi Gulf Coast during Hurricane Katrina, most of which was due to storm surge fatalities (National Oceanic and Atmospheric Administration 2006). The cost model results of using this fatality rate with the Hurricane Isabel+ data used in the previous section are indicated in Figure 26. The expected costs are much larger, and there is an evacuation signal at advisory 41. Recall from Chapter I that according to the American Society of Civil Engineers, 9 out of 10 storm related fatalities are a result of storm surge and coastal flooding. Increasing the expected fatalities to reflect the risk of storm surge changes the evacuation decision. The determination that ENCMCFI is not in an area at large risk due to storm surge is a result of the SLOSH model analysis by NOAA. These

models are constantly being updated and should their analysis of the storm surge potential at ENCMCFI change; the appropriate rates would need to be included in the model to reflect the true risks involved.

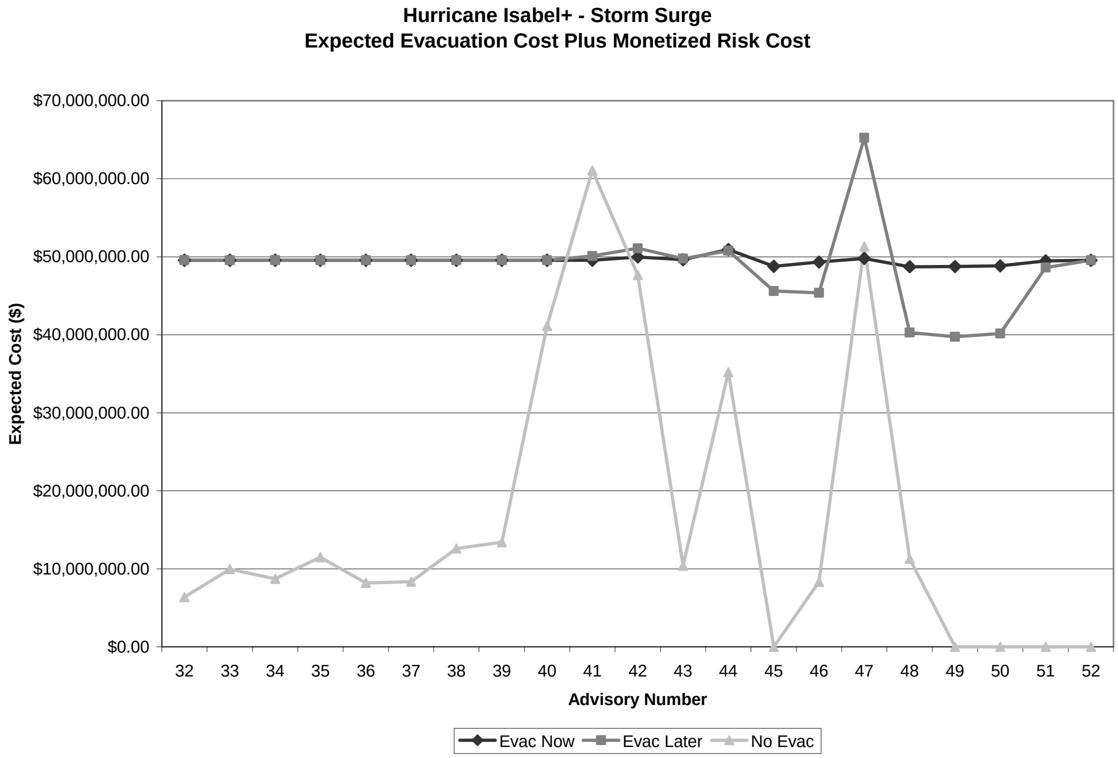

Figure 26. Hurricane Isabel+, expected transportation and monetized risk costs with larger storm surge fatality rate

The fatality model output shows a very different set of results from the non-storm surge numbers. The risk of remaining in an area exposed to a storm of this magnitude is apparent early in the forecast cycle. The expected fatality cost of never evacuating is roughly 5 times that of evacuation at any given forecast time, with a maximum difference of approximately 50 expected fatalities. The large expected number of fatalities in the evacuation decisions comes from the probability that all of the ENCMCFI population will not be able to evacuate, and will be subject to the storm effects. These evacuation decisions result in non-zero transportation risk costs and storm risk costs in both the cost of evacuation at the current forecast, and in the decision to wait 6 hours.

The larger expected number of fatalities is expected because storm surge places anyone who may ride out a major hurricane at risk. Part of the reason that the cost model expected fatalities results are in such discord with the is the relatively low value that the DoD uses for calculating risk to human lives.

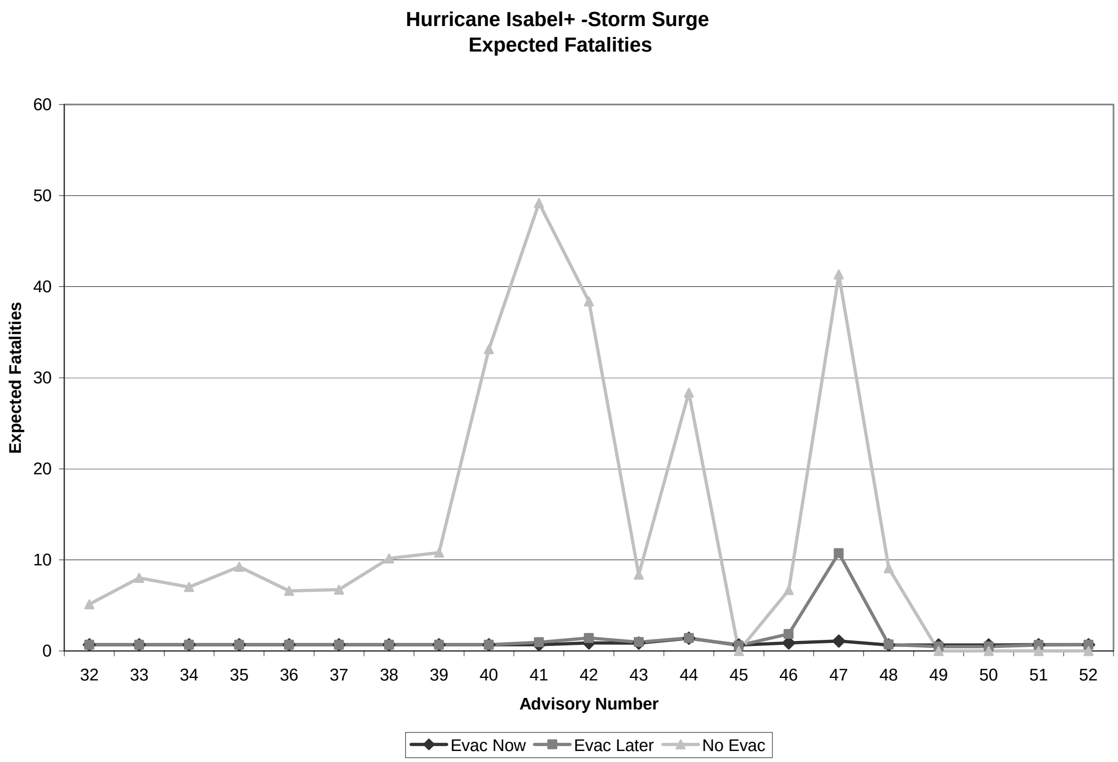

Figure 27. Hurricane Isabel+, expected fatalities – large storm surge fatality rate

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The analysis of the model output in Chapter IV has important implications for the hurricane evacuation decision of ENCMCFI. Based on this analysis, three conclusions can be made:

1. Based on the small storm surge risk at ENCMCFI, an ordered full evacuation of ENCMCFI personnel is not the best option due to ENCMCFI's protected location and relatively low risk of storm-related fatalities.
2. If the estimated risk of storm surge at ENCMCFI should increase, the evacuation decision process must be re-analyzed.
3. The results of this model are sensitive to the monetary value placed on the expected number of fatalities

These conclusions will be discussed in further detail in this chapter.

1. An Ordered Full Evacuation of ENCMCFI Personnel is Not the Best Option Due to ENCMCFI's Location and Relative Risk

Using the information from the analysis of the enhanced historical storms Hurricane Floyd+ and Hurricane Isabel+ in Chapter IV, the signal to evacuate from the model is never strong enough to indicate an evacuation. In both of these storms, the cost model did not indicate that evacuation was necessary, and the expected fatality risk model indicated only very small differences between evacuating and not evacuating. This result is peculiar to the location of ENCMCFI and their low risk from the effects of coastal flooding and storm surge. The occurrences of 105 kts winds being at ENCMCFI at different times are assumed to be conditionally independent given the forecasts of positions and intensities at those times. Using the non-storm-surge effects rates, even in

the worst case storm, the risks of evacuating are only marginally smaller than not evacuating at all (4.5 expected fatalities from storm risk vs. 0.8 expected fatalities for evacuating).

When the analysis is performed using a fatality risk rate that includes the possibility of storm surge related deaths, the evacuation decision is very different. The expected cost model does not indicate that an evacuation is warranted in the Hurricane Isabel+ case, but the expected fatality model indicates that evacuation is warranted. This disparity between the storm surge results and the non-storm surge results highlights sensitivity to the fatality rate. Under the assumption that the current SLOSH model results at ENCMCFI are correct, an evacuation is not warranted.

This thesis modeled the evacuation with a positive move population of 11,300 personnel. This number could increase to as many as 18,000 personnel, requiring five evacuation waves to move all of these personnel. This additional lead time will push the evacuation decision back to a time period when the forecast accuracy is not good enough to make evacuation decisions. Should ENCMCFI encounter this scenario, the first evacuation decision will have to be made no later than approximately 60 hours prior to the arrival of 34 kts winds.

2. If the Estimated Risk of Storm Surge at ENCMCFI Should Increase, the Evacuation Decision Process Must be Re-Analyzed

The conclusion that ENCMCFI is not in the primary risk zone for storm surge is a critical part of this analysis. These estimates are based on results from the SLOSH models from NOAA. The models are reanalyzed continually based verification of forecasts compared to actual storms. The SLOSH model is described in detail in Chapter I. If the SLOSH model changes to indicate that ENCMCFI is in fact in a region susceptible to storm surge flooding, then the evacuation decision model must be re-evaluated to determine an appropriate risk rate.

3. The Results of this Model are Sensitive to the Monetary Value Placed on the Expected Number of Fatalities

The analysis highlighted a sensitivity of the model to the cost of expected fatalities. The DoD Instruction 6055.7 values are much lower than those used by other government agencies such as the Environmental Protection Agency and the Federal Railroad Administration (Office of Management and Budget, 2000). Figure 28 illustrates this sensitivity by applying different fatality costs to the model at advisory 47 of Hurricane Isabel+ using the storm surge fatality rate. The fatality cost ($625,000) is multiplied by the factor on the x axis. With just two times the DoD 6055.7 value, there is a different evacuation signal, and the results increase with the multiplier.

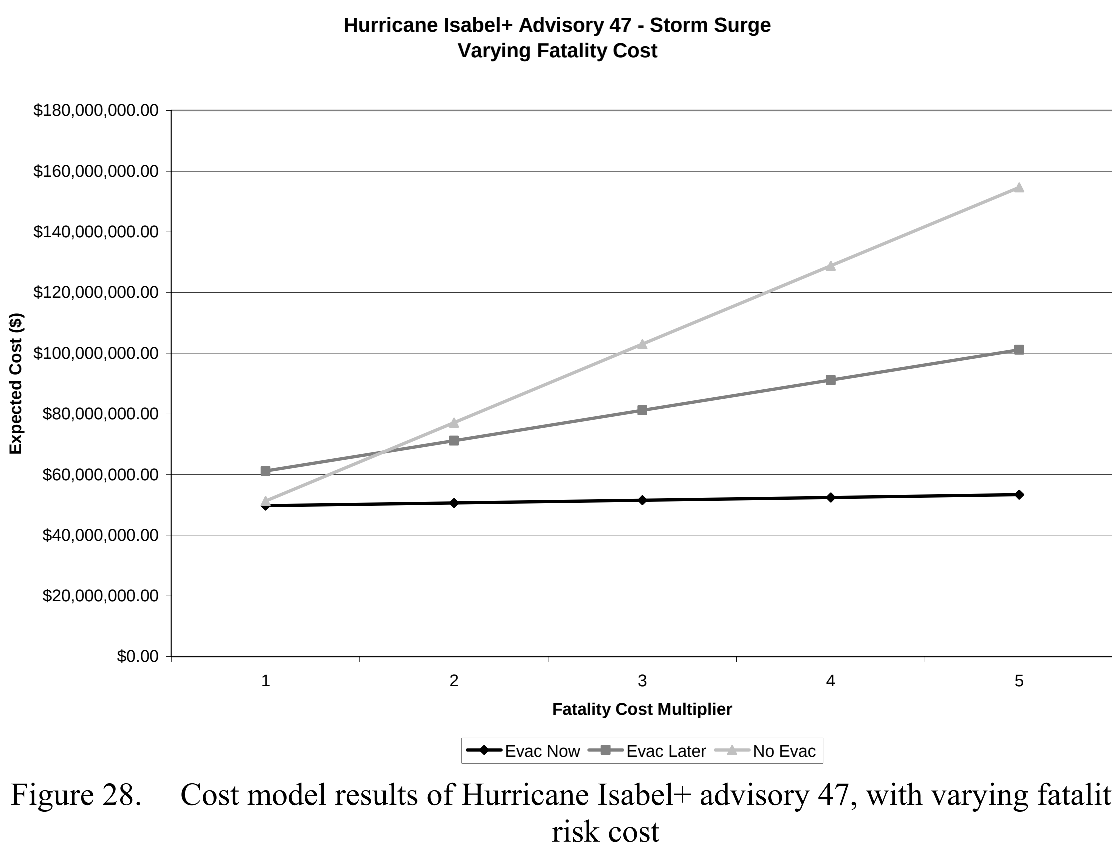

Figure 28. Cost model results of Hurricane Isabel+ advisory 47, with varying fatality risk cost

Rather than using expected costs, a better indicator of the relative risk is the expected evacuation fatalities at a given forecast time compared to the expected fatalities when starting evacuation at the next forecast time or not evacuating at all. While this result would incur sensitivity to the risk parameters, it produces more valid estimates.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

An analysis of storms using storm tracks rather than position and intensity at independent discrete forecast times may provide better insight into the actual motion of hurricanes. This thesis uses a model that treats the winds occurring at ENCMCFI at each individual forecast time as conditionally independent random variables given the forecast; in reality these hurricanes move in tracks that tie these positions together. A study of the historical tracks of hurricanes could provide a better estimate of the probability of extreme conditions occurring at ENCMCFI.

Another valuable area of study would be a more complete analysis of fatalities and injuries due to both hurricane storm effects and from evacuation transportation. Since the results of the model developed in this thesis are sensitive to changes in the estimated fatality and injury rates, a closer investigation of these rates would produce a more valid model. The creation of a model that relates storm risk rates to the category of hurricane and the cause of death or injury, whether from wind effects or storm surge, would produce the ability to custom tailor model results based on different categories of hurricanes. Such a model would enable decisions makers to have different evacuation scenarios for different levels of storms. By contrast this model includes only two storm conditions: less than or greater than 105 kts winds at ENCMCFI.

Since the transportation risk numbers used in this thesis were taken from non-evacuation figures, a more complete analysis of the hazards of evacuating would shed light on the evacuation decision and would provide better input data to the model.

Evaluating the model across all parameter ranges would provide greater insight into the ranges of model output values. This analysis only varied the rates based on storm surge effects and fatality costs. Further research into the ranges of the model parameters and the model's sensitivity to those changes would be insightful. Through

this further study, moments could be generated for model input parameters enabling probabilistic input. With data to support representing enough parameters as distributions, model output could be described with confidence intervals. This representation would better capture the stochastic nature of the problem.

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APPENDIX

A. HURRICANE FLOYD INTENSITY FORECAST

Hurricane Floyd

		Forecast Lead Time					
Adv #	Forecast Time:	0	12	24	36	48	72
1	1999-09-07T18:00	25	30	35	45	55	75
2	1999-09-08T00:00	30	40	50	60	70	80
3	1999-09-08T06:00	35	45	55	65	75	90
4	1999-09-08T12:00	40	45	55	65	75	90
5	1999-09-08T18:00	45	50	60	70	80	90
6	1999-09-09T00:00	45	60	70	80	90	95
7	1999-09-09T06:00	45	60	70	80	90	95
8	1999-09-09T12:00	50	60	70	80	90	95
9	1999-09-09T18:00	60	60	70	80	90	100
10	1999-09-10T00:00	60	60	70	80	90	100
11	1999-09-10T06:00	60	70	75	80	85	100
12	1999-09-10T12:00	70	80	85	90	95	105
13	1999-09-10T18:00	70	80	85	90	95	105
14	1999-09-11T00:00	80	80	80	85	95	105
15	1999-09-11T06:00	95	90	90	90	95	105
16	1999-09-11T12:00	95	95	95	95	100	105
17	1999-09-11T18:00	90	95	100	105	110	110
18	1999-09-12T00:00	85	95	100	105	110	110
19	1999-09-12T06:00	95	100	100	105	110	110
20	1999-09-12T12:00	105	110	115	120	120	120
21	1999-09-12T18:00	115	120	120	120	120	120
22	1999-09-13T00:00	125	130	135	135	130	125
23	1999-09-13T06:00	135	135	135	135	130	125
24	1999-09-13T12:00	135	135	135	135	135	65
25	1999-09-13T18:00	125	135	135	135	135	50
26	1999-09-14T00:00	115	135	135	125	120	50
27	1999-09-14T06:00	105	135	130	125	120	50
28	1999-09-14T12:00	105	125	125	125	120	40
29	1999-09-14T18:00	110	120	120	120	65	45
30	1999-09-15T00:00	115	120	120	110	60	45
31	1999-09-15T06:00	110	120	120	65	55	45
32	1999-09-15T12:00	100	110	75	55	45	45
33	1999-09-15T18:00	95	95	70	60	45	45
34	1999-09-16T00:00	90	85	60	50	50	50
35	1999-09-16T06:00	90	80	65	50	50	50
36	1999-09-16T12:00	70	60	50	50	50	50
37	1999-09-16T18:00	60	50	45	45	45	45

38	1999-09-17T00:00	50	45	45	45	45	45
39	1999-09-17T06:00	50	50	50	50	50	50

(National Weather Service, National Hurricane Center, 2007a)

B HURRICANE FLOYD+ INTENSITY FORECAST

Hurricane Floyd+

		Forecast Lead Time					
Adv #	Forecast Time:	0	12	24	36	48	72
1	1999-09-07T18:00	25	30	35	45	55	75
2	1999-09-08T00:00	30	40	50	60	70	80
3	1999-09-08T06:00	35	45	55	65	75	90
4	1999-09-08T12:00	40	45	55	65	75	90
5	1999-09-08T18:00	45	50	60	70	80	90
6	1999-09-09T00:00	45	60	70	80	90	95
7	1999-09-09T06:00	45	60	70	80	90	95
8	1999-09-09T12:00	50	60	70	80	90	95
9	1999-09-09T18:00	60	60	70	80	90	100
10	1999-09-10T00:00	60	60	70	80	90	100
11	1999-09-10T06:00	60	70	75	80	85	100
12	1999-09-10T12:00	70	80	85	90	95	105
13	1999-09-10T18:00	70	80	85	90	95	105
14	1999-09-11T00:00	80	80	80	85	95	105
15	1999-09-11T06:00	95	90	90	90	95	105
16	1999-09-11T12:00	95	95	95	95	100	105
17	1999-09-11T18:00	90	95	100	105	110	110
18	1999-09-12T00:00	85	95	100	105	110	110
19	1999-09-12T06:00	95	100	100	105	110	110
20	1999-09-12T12:00	105	110	115	120	120	120
21	1999-09-12T18:00	115	120	120	120	120	120
22	1999-09-13T00:00	125	130	135	135	130	125
23	1999-09-13T06:00	135	135	135	135	130	125
24	1999-09-13T12:00	135	135	135	135	135	135
25	1999-09-13T18:00	145	140	135	130	125	115
26	1999-09-14T00:00	140	130	135	130	125	115
27	1999-09-14T06:00	140	130	135	130	125	115
28	1999-09-14T12:00	140	135	135	135	130	125
29	1999-09-14T18:00	140	140	135	135	130	125
30	1999-09-15T00:00	135	135	130	130	130	125
31	1999-09-15T06:00	130	130	130	130	130	120
32	1999-09-15T12:00	135	135	135	130	130	125
33	1999-09-15T18:00	140	140	140	135	135	130
34	1999-09-16T00:00	135	135	130	130	130	125
35	1999-09-16T06:00	130	130	130	130	130	120
36	1999-09-16T12:00	135	135	135	130	130	125
37	1999-09-16T18:00	140	140	140	135	135	130
38	1999-09-17T00:00	50	45	45	45	45	45
39	1999-09-17T06:00	50	50	50	50	50	50

(National Weather Service, National Hurricane Center, 2007a)

C HURRICANE ISABEL INTENSITY FORECAST

Hurricane Isabel

		Forecast Lead Time							
Adv #	Forecast Time:	0	12	24	36	48	72	96	120
1	2003-09-06T06:00	35	40	45	55	65	65	35	40
2	2003-09-06T12:00	40	40	45	55	65	65	40	40
3	2003-09-06T18:00	45	50	60	65	70	75	45	50
4	2003-09-07T00:00	55	60	65	70	75	80	55	60
5	2003-09-07T06:00	60	60	65	70	75	85	60	60
6	2003-09-07T12:00	65	75	85	95	100	100	65	75
7	2003-09-07T18:00	70	75	85	95	100	100	70	75
8	2003-09-08T00:00	80	85	90	95	100	100	80	85
9	2003-09-08T06:00	95	100	105	110	115	115	95	100
10	2003-09-08T12:00	110	115	120	120	120	120	110	115
11	2003-09-08T18:00	110	120	125	125	125	125	110	120
12	2003-09-09T00:00	115	120	125	120	115	110	115	120
13	2003-09-09T06:00	115	120	125	120	115	110	115	120
14	2003-09-09T12:00	115	120	125	120	115	115	115	120
15	2003-09-09T18:00	115	120	125	120	115	115	115	120
16	2003-09-10T00:00	110	115	115	115	115	115	110	115
17	2003-09-10T06:00	110	115	115	115	115	115	110	115
18	2003-09-10T12:00	115	115	115	115	115	115	115	115
19	2003-09-10T18:00	120	125	120	120	120	115	120	125
20	2003-09-11T00:00	125	125	125	120	120	115	125	125
21	2003-09-11T06:00	125	125	125	120	120	115	125	125
22	2003-09-11T12:00	135	130	130	125	120	115	135	130
23	2003-09-11T18:00	145	140	135	130	125	115	145	140
24	2003-09-12T00:00	140	130	135	130	125	115	140	130
25	2003-09-12T06:00	140	130	135	130	125	115	140	130
26	2003-09-12T12:00	140	135	135	135	130	125	140	135
27	2003-09-12T18:00	140	140	135	135	130	125	140	140
28	2003-09-13T00:00	135	135	130	130	130	125	135	135
29	2003-09-13T06:00	130	130	130	130	130	120	130	130
30	2003-09-13T12:00	135	135	135	130	130	125	135	135
31	2003-09-13T18:00	140	140	140	135	135	130	140	140
32	2003-09-14T00:00	135	140	135	130	125	120	135	140
33	2003-09-14T06:00	135	140	135	130	125	120	135	140
34	2003-09-14T12:00	135	135	135	130	125	120	135	135
35	2003-09-14T18:00	140	135	135	130	125	120	140	135
36	2003-09-15T00:00	130	135	130	125	120	115	130	135
37	2003-09-15T06:00	125	130	130	125	120	115	125	130
38	2003-09-15T12:00	120	115	115	115	115	110	120	115
39	2003-09-15T18:00	115	110	105	105	105	100	115	110
40	2003-09-16T00:00	105	105	100	100	100	60	105	105
41	2003-09-16T06:00	100	100	100	100	100	55	100	100

42	2003-09-16T12:00	95	85	85	90	95	45	95	85
43	2003-09-16T18:00	95	90	90	90	95	30	95	90
44	2003-09-17T00:00	95	95	95	95	65	40	95	95
45	2003-09-17T06:00	95	95	95	95	60	35	95	95
46	2003-09-17T12:00	90	95	95	70	50	30	90	95
47	2003-09-17T18:00	90	95	95	60	40	30	90	95
48	2003-09-18T00:00	90	95	65	50	40	30	90	95
49	2003-09-18T06:00	90	90	60	45	35	30	90	90
50	2003-09-18T12:00	90	65	45	30	30	0	90	65
51	2003-09-18T18:00	85	55	35	30	25	0	85	55
52	2003-09-19T00:00	65	40	30	25	25	0	65	40
53	2003-09-19T06:00	50	35	30	25	25	0	50	35
54	2003-09-19T12:00	35	35	35	35	0	0	35	35

(National Weather Service, National Hurricane Center, 2007a)

D HURRICANE ISABEL+ INTENSITY FORECAST

Hurricane Isabel+									
		Forecast Lead Time							
Adv #	Forecast Time:	0	12	24	36	48	72	96	120
31	2003-09-13T18:00	140	140	140	135	135	130	125	105
32	2003-09-14T00:00	135	140	135	130	125	120	110	100
33	2003-09-14T06:00	135	140	135	130	125	120	110	100
34	2003-09-14T12:00	135	135	135	130	125	120	110	70
35	2003-09-14T18:00	140	135	135	130	125	120	105	35
36	2003-09-15T00:00	130	135	130	125	120	115	90	35
37	2003-09-15T06:00	125	130	130	125	120	115	60	35
38	2003-09-15T12:00	120	115	115	115	115	110	60	30
39	2003-09-15T18:00	115	110	105	105	105	100	50	30
40	2003-09-16T00:00	135	135	135	130	130	125	120	110
41	2003-09-16T06:00	140	140	140	135	135	130	125	105
42	2003-09-16T12:00	115	115	115	115	115	115	110	110
43	2003-09-16T18:00	120	125	120	120	120	115	115	115
44	2003-09-17T00:00	125	125	125	120	120	115	115	115
45	2003-09-17T06:00	125	125	125	120	120	115	115	115
46	2003-09-17T12:00	135	130	130	125	120	115	115	115
47	2003-09-17T18:00	145	140	135	130	125	115	115	115
48	2003-09-18T00:00	140	130	135	130	125	115	115	110
49	2003-09-18T06:00	140	130	135	130	125	115	115	110
50	2003-09-18T12:00	140	135	135	135	130	125	110	105
51	2003-09-18T18:00	140	140	135	135	130	125	115	105
52	2003-09-19T00:00	135	135	130	130	130	125	115	105

(National Weather Service, National Hurricane Center, 2007a)

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